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# Enabling Industrial Symbiosis in Industrial Parks

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May you all be filled with love, peace and happiness.

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## List of Abbreviations

| | |
|---|---|
| IP | Industrial Park |
| IS | Industrial Symbiosis |
| IT | Information Technology |
| RE | Requirements Engineering |

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## 1. Introduction & Research Motivation

Human activities have become a major driver of global change, so that global society and economy are facing consequences such as climate change, increasing scarcity of resources, environmental pollution and degradation as well as disturbances of ecosystem functioning and services. Today's era is called "the Anthropocene" due to its human-dominated global impacts (Crutzen, 2002), in which planetary boundaries are transgressed continuously (Rockström et al., 2009). In order to meet these main challenges in an appropriate way, adequate starting points and solutions must be pursued at all levels to shift the current socio-economic pathway from an unsustainable to a safe operating and thus sustainable development within the planetary boundaries. The reduction of waste, emissions, primary resource and energy consumption, among many others, are considered to be fields of action for sustainable development (EEA, 2016). So concepts such as circular economy and resource efficiency are taking high priorities on the European Union (EU) policy agenda (EEA, 2016).

One of the application concepts in industrial contexts is Industrial Symbiosis (IS), which deals with the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple material and energetic (re-)utilization within industrial systems in order to increase resource productivity and efficiency, while reducing environmental impacts. "Industrial symbiosis, as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. (…) Industrial symbiosis engages traditionally separated industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and synergistic possibilities offered by geographic proximity" (Chertow, 2000, p. 313–314). Li (2018) defines IS as the exploration of "ways to establish knowledge webs of novel material, energy, and waste exchanges and business core processes to facilitate the development of networks of synergies within and across different companies to support the development of high levels of nearly closed-loop material exchanges and efficiency of energy cascading within and across industrial ecosystems" (Li, 2018, p. 35). According to Lombardi and Laybourn (2012), "IS engages diverse organizations in a network to foster eco innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes".

Industrial Symbiosis (IS) provides a vast potential for organizations to improve their economic, technical and ecological performance by connecting the supply and demand of various industries (Chertow, 2000; Van Capelleveen et al., 2018). Cross-sectoral collaboration within an IS community is required in order to exchange materials, energy, water and human resources. So when considering an evolution of an IS system, one can disentangle various layers, in this study, four layers were differentiated: the triggering, enabling, operating and performance improvement layer (Fig. 1).

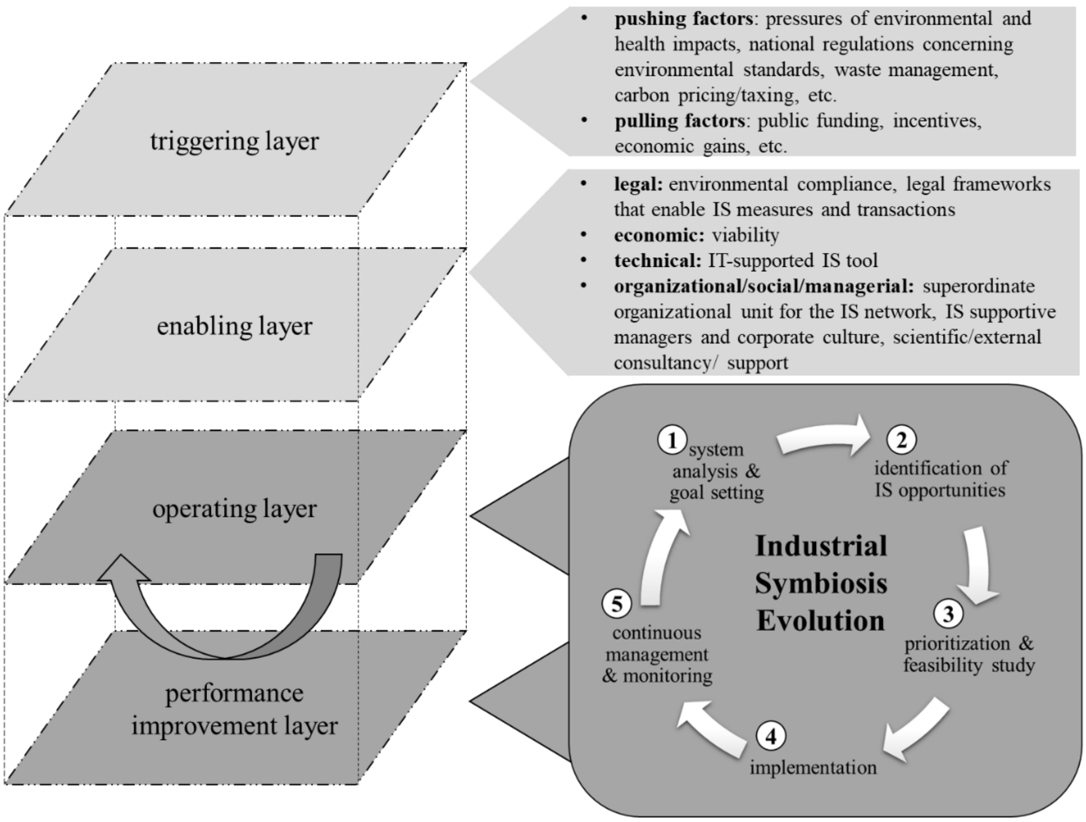


**Fig. 1:** Overview scheme of the evolution of an IS system.

Triggering factors for the evolution of IS systems comprise two categories: pushing (pressures of environmental and health impacts, national regulations concerning environmental standards, waste management, carbon pricing/taxing, etc.) and pulling factors (public funding, incentives, etc.).

The enabling layer covers the legal frameworks that can enable but also hinder IS measures, the economic viability, which also limits the implementation of IS activities, the organizational/managerial and technical factors. Taddeo et al. (2017) studied the Abruzzo Region in Italy and stated, that from the analysis of the current state of the IS context, technical factors (structural and other contingent factors) emerge as relevant, but also non-technical factors (existing relations and local community) may greatly influence the IS development. The success of the IS evolution is highly depend on the level of trust, motivation/interests, willingness, readiness and openness of the entities involved, so beside the most known primary economic motivation (Heeres et al., 2004; Jackson & Clift, 1998; Senlier & Albayrak, 2011; Sakr et al., 2011), the social, ethical and organizational factors are the crucial driving forces to exploit the full potential of IS.

The operating and performance improvement layer of the IS system follow the continuous improvement process of the principle of PDCA (Plan-Do-Check-Act). The process of identifying IS opportunities can be conducted by various quantitative methods which will be presented in chapter 3. First of all, all involved entities need to be identified and the actual state of the system needs to be analyzed with appropriate methods in order to detect potential supply-demand matchings and other infrastructure and utility synergies. Afterwards the identified IS activities can be analyzed and prioritized concerning technical, economic, regulatory, environmental, social, temporal and spatial aspects. This also includes feasibility, resilience and vulnerability studies. The chosen measures can then be implemented and the existing entities linked and/or new elements (e.g. enterprises) added to the IS system. The performance progress should be continuously analyzed, monitored and controlled, which an established superordinate organizational unit can manage and push the IS activities towards the defined goals, while simultaneously assist to reduce potential risks/barriers and vulnerabilities, increase the resilience of the IS system and exhaust full potential of IS opportunities taking into account legal and economic feasibility.

Especially environmental regulations and laws are considered to be triggering and pushing forces for companies to engage in an IS system (Bacudio et al. 2016; Ji et al. 2020), beside the motivation of economic advantages. Among others, hindering factors are the lack of awareness of IS concepts (Sakr et al. 2011; Bacudio et al. 2016; Ji et al. 2020), lack of local IS possibilities, lack of information sharing among locators (Sakr et al. 2011; Bacudio et al. 2016), lack of an institutional support for integration, coordination and communication, lack of technology and infrastructure readiness (Bacudio et al. 2016). The identified barriers of IS implementation had driven this research work, which aims to tackle these aspects and facilitate the exploitation of IS to be used as a lever for a sustainable industrial development. That is the reason why this research work focuses on the enabling layer, especially on the technical aspect of an IT-supported IS tool. Usually IS ties are connected between organizations of different industrial sectors which have not entered into a customer-supplier business relation yet (Herczeg et al., 2016), therefore IS synergies between companies only can be identified when an inter-organizational cooperation and communication is supported (Heeres et al., 2004; Ismail, 2014). So an information system can serve as a facilitator of communication and distributor of knowledge, while providing cross-organizational access and information sharing (Sakr et al. 2011; Isenmann, 2013; Song et al., 2018). One of the essential technology-enabled factors is the establishment of an information platform, which provides an integrated analysis tool for the industrial park itself in order to add the functions of identification of IS opportunities, IS performance monitoring and community and trust building.

## 2. Research Design & Objectives of the Cumulative Dissertation

The overarching goal of the research project was to identify and develop approaches to enable the evolution of Industrial Symbiosis (IS) in Industrial Parks (IPs). The research project was conducted in a transdisciplinary research mode (according to Lang et al., 2012). Therefore, the research design was based on the three guardrails of system knowledge, transformative knowledge and normative knowledge, from which the research questions were derived, as displayed in Fig. 2.

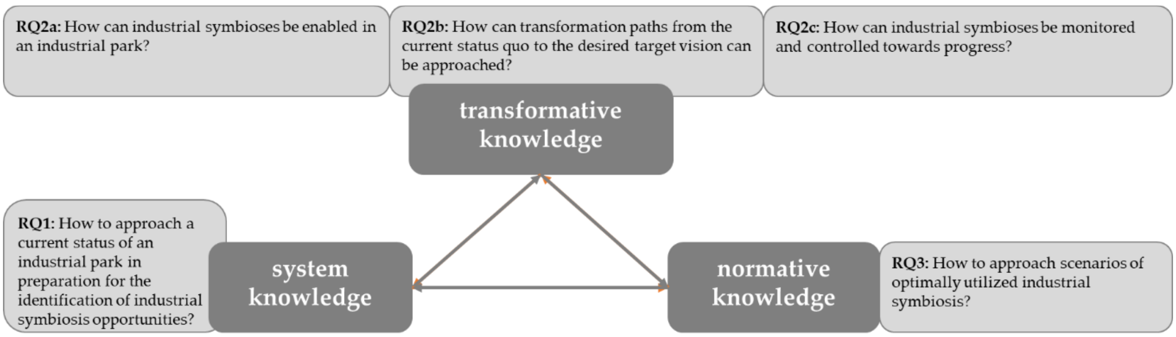


**Fig. 2:** Guiding research questions.

The research project was divided up into four research phases in a cascading and iterative exploration manner (Fig. 3). The aim of research phase 1 was to gain more systematic insights for the part of system knowledge and to converge to possible answers of the research question (RQ1): How to approach a current status of an industrial park in preparation for the identification of industrial symbiosis opportunities? Therefore, a comprehensive systematic literature review, employing bibliometric analysis and snowballing techniques, was carried out to select a total of 105 freely accessible papers and an explorative cross-case analysis was conducted by investigating 80 IS case studies in depth. Case studies were chosen with the non-probability sampling technique of purposive sampling. The initial sample size was predetermined. The processes of qualitative data collection and analysis were conducted simultaneously. As a purposive sampling technique, the maximum variation sampling was applied in order to cover a wide range of perspectives and IS case studies, enabling the examination of software requirements and IS patterns across the sample case. When selecting the case studies, consideration was given to addressing a diverse set of different IS systems. Additionally, it was ensured to collect case studies from different periods, authors and geographical regions. Publications were sourced from the following databases, such as Thomson Reuters Web of Knowledge, ResearchGate, google scholar, Scopus, CORE, and Directory of Open Access Journals. Only publications in English and German were included in the study due to reasons of language comprehension.

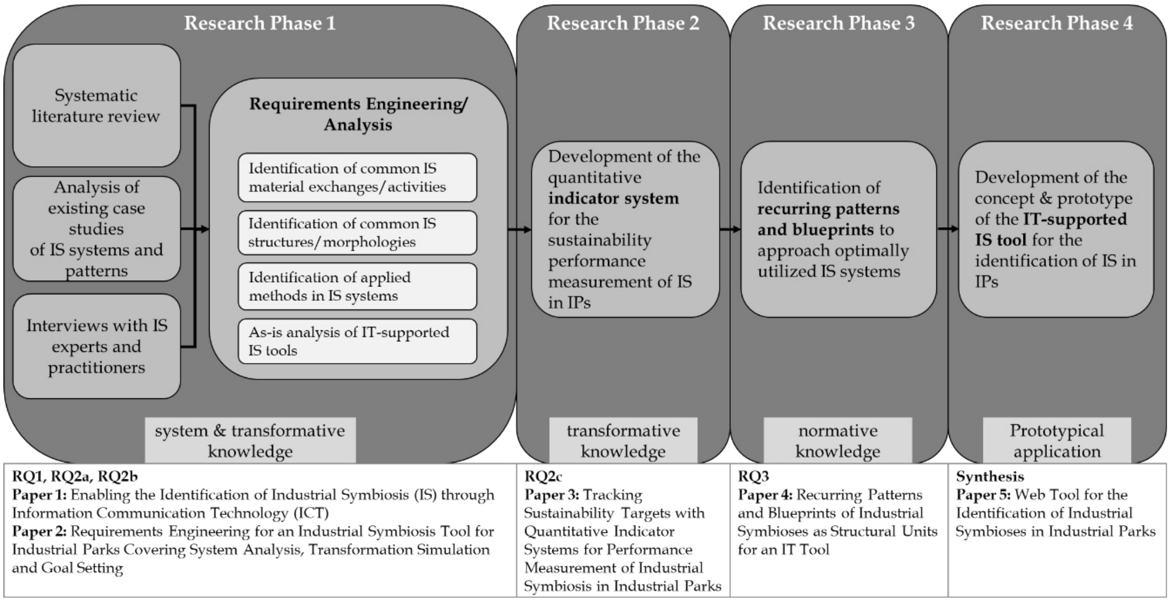


**Fig. 3:** Research design.

Additionally, a short survey and informal interviews with IS experts and practitioners served to weave practical and pragmatic knowledge and experience into the phase of Requirements Engineering (RE), wherein the basic concept for an IT-supported IS tool was developed. In this context, 37 experts and practitioners from the sectors consultancy, energy and raw materials industry, chemical/pharmaceutical industry, public administration/authority, resource and waste management, automotive and construction industry were involved. The interviewees came from Germany, Netherland, Denmark, Norway and Northern Ireland and worked at management and advisory level. They had practical experience with IS so far because they were involved in an advisory function or their company is or was part of an IS system. Requirements Engineering (RE), also called requirements analysis, is one of the main activities of the software or system development process, which defines the requirements for the system to be developed with the help of a systematic procedure from the project idea of the goals to a complete set of requirements. This was complemented by an extensive research to identify common IS material exchanges and activities, IS structures and morphologies and applied (research) methods for the identification of IS opportunities. Furthermore, an as-is analysis of IT-supported IS tools was carried out to build on existing knowledge and further develop and refine the concept of a new IT-supported IS tool to enable IS evolution in industrial parks.

Research Phase 2 addresses the development of a quantitative indicator system for the sustainability performance measurement of IS systems as an essential part of gaining transformative knowledge, in which the following research questions were approached:

RQ2a: How can industrial symbioses be enabled in an industrial park?

RQ2b: How can transformation paths from the current status quo to the desired target vision can be approached?

RQ2c: How can industrial symbioses be monitored and controlled towards progress?

In research phase 3 the normative knowledge was approximated by the identification of recurring patterns and blueprints of optimally utilized IS systems in order to converge to possible answers of RQ3: How to approach scenarios of optimally utilized industrial symbiosis?

The final research phase 4 culminated in a first prototypical concept for an IT-supported IS tool for enabling IS evolution in industrial parks.

## 3. Summary of the main research results of the published, peer-reviewed work of the cumulative dissertation

The results of the expert and practitioner interviews and survey were incorporated in the conceptualization of a prototypical IT-supported IS tool. Fig. 4 shows the expert and practitioner perception of the relevance of each displayed triggering and driving factors of IS. This results confirm that the main motivation of initiating and implementing IS is driven by economic factors such as rising resource and raw material prices, cost savings due to inter alia reduced disposal costs, increase of resource and energy efficiency as well as resource productivity and legal regulations/compliance issues.

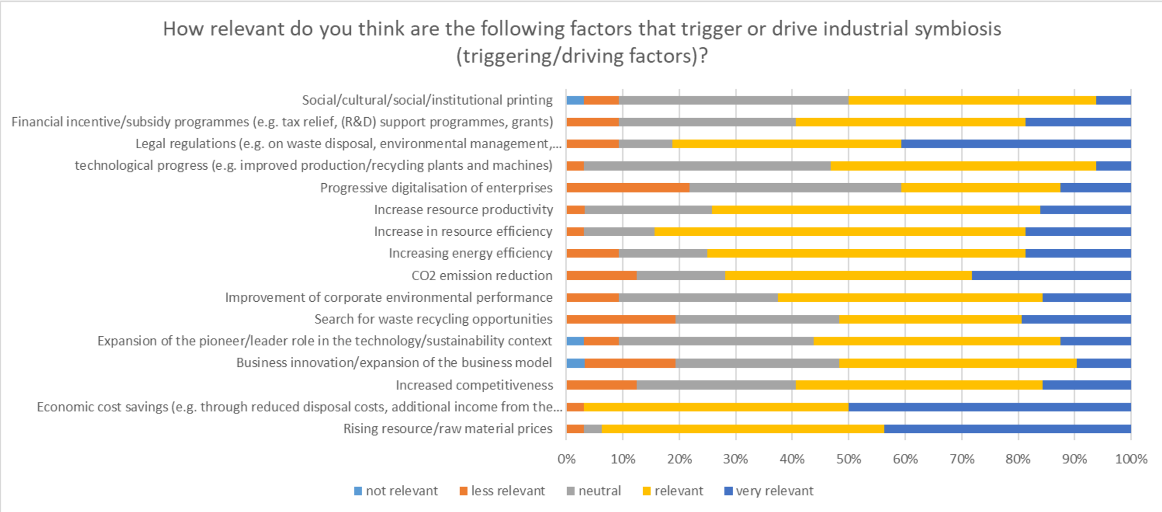


**Fig. 4:** Survey results for triggering and driving factors of IS.

Fig. 5 presents the expert and practitioner perception of the relevance of each displayed limiting factors of IS that complicate or hinder an IS between different companies. The most significant trends of IS barriers were judged to be economic aspects such as the focus on the core business and consequently existing forces for business-as-usual/reluctance of change, competition and additional resource expenditures. Noteworthy in this context is, that a main barrier was also considered to be a lack of information and knowledge about possible IS measures.

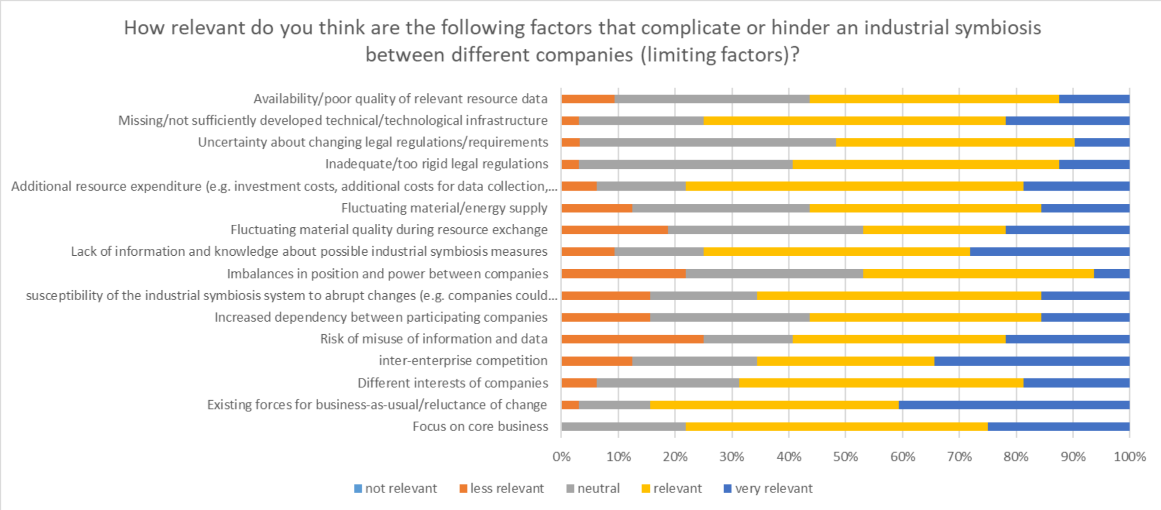


**Fig. 5:** Survey results for limiting factors of IS.

Fig. 6 reflects the expert and practitioner perception of the relevance of each displayed feature that a software tool should cover in an IS context. The ranking of the relevance of the different tool functions indicates comparatively that the main focus is on identifying IS opportunities, managing IS activities and not on monitoring or reporting IS or sustainability performance.

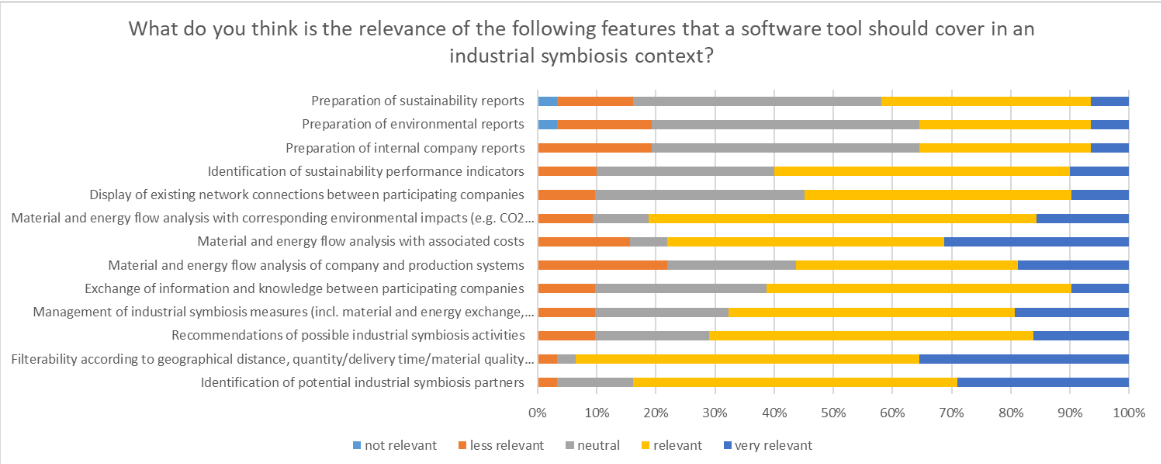


**Fig. 6:** Survey results for relevant aspects of a software tool in an IS context.

Traditionally, IS networks have been divided up into three main categories of exchange types: water, power (including heat) and materials (Kastner et al., 2015). The identification of IS potentials can be conducted by various quantitative methods. In this study, the methods of Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Social Network Analysis (SNA) were detected as the most applied methods in the IS context to reveal IS opportunities and analyze the actual state of an IS system. Other researchers confirm these findings very close to congruent (Li et al., 2017; Kastner et al., 2015; Huang et al., 2019): the most widely applications are MFA (Geng et al., 2012; Sendra et al., 2007; Yong et al., 2009), LCA (Sokka et al., 2010; Sokka et al., 2011), and environmental indicators (Kurup & Stehlik, 2009; Pakarinen et al., 2010; Zhu et al., 2010). Which methods are considered for which purpose and for which context? This needs to be differentiated when applying various methods for the IS identification, IS performance measurement and the investigation of existing IS systems concerning inter alia the structure and morphology, etc.

MFA quantifies the flows and stocks of materials and energy of the system under consideration in physical units (e.g., kg), distinguishing between input and output streams of the respective processes. This method is applied to material and energy flows, crossing exchange type boundaries (water, power, materials) and is a first starting point to visualize the (production) system with its respective input and output flows and screen first possible IS matchings.

LCA quantifies the flows and stocks of materials and energy of the system under consideration and assesses the associated environmental impacts, such as global warming and eutrophication potential. LCA is based on the method of MFA and applicable to material, water and energy flows. This method considers all exchange type boundaries throughout an entire product life cycle (from raw material extraction, production, distribution/retail, to usage and disposal) and assesses the environmental impacts of products and services.

SNA investigates social structures of networks and characterizes elements within the network in terms of nodes (e.g., individual actors, companies, people) and the connecting tie or links (relationships or interactions). SNA analyzes the characteristics, power quantification and structure of the IS network and can provide insights for understanding the social aspects of an IS system and how (social) business relationships drive the exchanges of materials, energy and information.

Many Information Communication Technology (ICT) tools have been developed to facilitate IS, but they predominantly focus on the as-is analysis of the IS system

(Grant et al., 2010; Maqbool et al., 2019). The main focus is on the identification of possible IS measures and (the management of) material and energy exchanges by output-input matching of various resource flows among companies, functionality and technical opportunities (Grant et al., 2010). Furthermore, decision support such as advanced analysis regarding economic viability of different IS activities (Raabe et al., 2017) and ecological impacts (reduction) are not provided. Additionally, the development of a common desired target vision for an IP or corresponding possible future scenarios as well as conceivable transformation paths from the actual state to the desired target vision are not taken into account. This gap shall be addressed in this research work, presenting the requirements engineering results for a conceptual IT-supported IS tool. This new approach goes beyond as-is and system analysis and includes the use of system dynamics and Artificial Intelligence (AI) techniques, which turn the IT-supported IS tool into a comprehensive and holistic instrument with which future scenarios and transformation paths can be simulated.

For monitoring and controlling the development and progress of an IS system, an indicator system must be set up to standardize and assess the IS (sustainability) performance. Therefore, a quantitative indicator system was developed to enable the tracking of set sustainability targets of an IS system in Industrial Parks (IPs) for goal-directed IS management. The presented guiding framework encourages IP members in IS systems to set sustainability objectives and to evaluate and track their performance over time with a quantitative indicator system. In particular,established and (partly) internationally standardized methods—such as Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA), Social Network Analysis (SNA), and Life Cycle Assessment (LCA)—are used in order to place the indicator system on a solid and robust foundation and to adequately meet the multi-faceted sustainability perspectives in the form of a combinatorial application for deriving suitable quantitative indicators for all three (environmental, economic, social) dimensions of sustainability. The indicator system, once embedded in an Information Technology (IT)-supported IS tool, contributes crucially to the technology-enabled environment of IS systems, driving

sustainability trajectories.
Additionally, recurring patterns in IS systems of specific IS case studies were identified and elementary blueprints and structural units were deduced, setting an initial cornerstone to pool and synthesize existing IS knowledge and to deploy this knowledge base in an IT-supported IS tool, which would remarkably advance the scope of action and development of IS systems. Recurring (key) patterns in IS systems were illuminated by generalizing and abstracting IS main structures, compositions, resource exchange activities and measures.
It has been shown that similar IS sectoral partnerships and resource exchanges have recurrently formed in different regions and hence, generalizable patterns, elementary blueprints and structural units can be deduced from existing IS case studies. This work revealed that the fundamental functioning of an IS system mimics the essential mechanisms of ecological resource metabolisms, covering producers, primary/secondary/n consumers and destruents/remineralizers. The most frequent key sectors in IS systems comprise agriculture/aquaculture, power, pulp and paper, iron and steel, construction, chemical as well as waste treatment/recycling industries. Also repetitious resource exchanges and structural formations occurred in IS systems. This study identified common IS compositions, sector clusters and key/core/anchor entities and synthesized a content basis for a database of an IS resource exchange catalog based on existing/available IS information, which can be used in an IT-supported IS tool. It contains information of specific IS resource exchanges, broken down by industrial sectors, differentiating providing and receiving sectors and which respective exchanged waste flows were processed into which secondary material/product.
Once this fundamental information/data base is incorporated and applied in an IT-supported IS tool, it enables the facilitated recommendation of potential IS partners and IS actions to optimize existing IS cases or to initiate IS development and approach scenarios of optimally utilized IS systems. Especially, first IS germ cells of (key) entities can be derived and connected to each other considering individual circumstances and (geographical) business environments.

## 4. Paper 1: Enabling the Identification of Industrial Symbiosis (IS) through Information Communication Technology (ICT)

A. Lütje, M. Willenbacher, A. Möller, V. Wohlgemuth, “Enabling the Identification of Industrial Symbiosis (IS) through Information Communication Technology (ICT)”, 2019, Proceedings of the 52nd Hawaii International Conference on System Sciences (HICSS), pp. 709-719, ISBN: 978-0-9981331-2-6, doi: http://hdl.handle.net/10125/59511

For better readability, better understanding and a logical structure of the research work, the original publications are inserted in each case.

# Enabling the Identification of Industrial Symbiosis (IS) through Information Communication Technology (ICT)

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## Abstract

*Industrial Symbiosis (IS) is an emerging business tool with a systemic and collaborative approach to optimize and close cycles of materials and energy by identifying synergies and fostering cross-sectoral cooperation among economic actors. The major facilitator of revealing IS opportunities for organizations is both analyzing the status quo with quantitative methods and connecting the supply and demand of the entities involved through an adequate Information Communication Technology (ICT) solution. This study analyzed the extant body of literature and the corresponding ICT tools of IS in order to design a preliminary concept of an Information Technology (IT) supported IS tool that supports the identification and assessment of IS potentials, providing more transparency among market players and proposing potential cooperation partners according to selectable criteria (e.g. geographical radius, material properties, material quality, purchase quantity, delivery period), bringing synergy partners together.*

## 1. Introduction

Today´s era is called "the Anthropocene", human activities have become the main driver of global change such as climate change, environmental pollution and increasing scarcity of resources [1]. Especially a resource efficient circular economy contributes to a trajectory of sustainable development [2]. Industrial Symbiosis (IS) is considered to be a key enabling factor for resource efficiency, which takes an emerging priority on the European Union (EU) policy agenda [2].

Industrial Symbiosis (IS) falls under the umbrella of Industrial Ecology (IE) [3]. It is a systemic and collaborative business approach to optimize and close cycles of materials and energy while generating ecological, technical, social and economic benefits [3,4,5]. The most cited definition is from [3], "IS engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and byproducts." According to [6], "IS engages diverse organizations in a network to foster eco innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes."

Many IS networks exist across the globe, there are round about 121 case studies in Europe [7]. The most well known and analyzed IS network is located in Kalundborg (Denmark), where an Eco-Industrial Park (EIP) has emerged spontaneously [8]. EIPs have been investigated in various comparative studies, but mostly in developed countries, so there is a research gap concerning developing countries [61], although there is a modest number of published studies [50,51,60,61,65], while the tendency is increasing.

Industrial Parks (IPs) can contribute to regional and economic growth, but without considering environmental issues in a sophisticated and holistic manner into the planning and construction of IPs, economic gains can be generated in the short term,

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but come at a loss of disturbed ecosystem services and quality within and around the location of the IPs, which even can pose economic threats to the development of IPs in the long term due to possible water shortages, amongst others [61,62]. So potential negative feedback-loops need to be avoided in advance or at least slowed down or reduced, especially in emerging and developing countries where the growth of IPs is rapidly rising, as for example in China [62].

Each entity involved in the (Eco-)Industrial Park (EIP) can be considered as a node in a widely ramified network, so IPs could or should be seen as entire eco(sub-)systems [58], which are embedded in the overarching natural ecosystem [62]. Usually IS connections are built between organizations of different industrial sectors which have not entered into a customer-supplier business relation [5], therefore IS synergies between companies only can be identified when an inter-organizational cooperation and communication is supported [42]. So an information system can serve as a facilitator of communication and distributor of knowledge, while providing cross-organizational access and information exchange [9]. Many ICT tools have been developed to support the identification and expansion of IS, but most of them are no longer in use [15,43].

## 2. Literature Review

This study investigates retrospectively the extant body of literature of Industrial Symbiosis (IS) and the current state of IS tools in order to derive various implications for the advancement of ICT solutions in the context of IS and emerging and developing countries, proposing a preliminary concept for an IT-supported IS tool for the identification and assessment of IS opportunities based on a conducted systematic literature review. So this study was conducted to converge to possible answers to a certain extent of the following research questions: *How can industrial symbioses (IS) be identified and enhanced? (RQ1) How can an appropriate IT tool be designed? (RQ2)*

As there are several concepts of IS such as synergies among firms (e.g. along supply chains) that are not co-located or within one specific industrial branch (homogeneous setting), this study focuses on IS network expansion within existing industrial parks, so co-located firms across various industrial sectors (heterogeneous setting). The focal point is especially on the identification of synergies between factories with geographical proximity. In the literature, a clear distinction between designing a new industrial park and converting an existing industrial park into an Eco-Industrial Park (EIP) is rare [11]. This study concentrates on the scenario of retrofitting an existing industrial park to an EIP.

Publications were sourced from the following databases such as ResearchGate, google scholar, Thomson Reuters Web of Knowledge and the conference website of EnviroInfo. The queries search the following terms “industrial symbiosis“, “industrial symbiosis in developing countries”, “eco-industrial park“, “information systems”, “ICT tool” and its various combinations.

Based on the already collected scientific references, the snowballing technique, a backward and forward analysis based on the citations of the relevant publications was applied to identify further relevant literature. Only publications in English and German were included in the study.

## 3. Facilitating Industrial Symbiosis

### 3.1. Quantitative Methods & Case Studies

Industrial Symbiosis (IS) reveals opportunities for organizations to improve their economic, technical and ecological performance by connecting the supply and demand of various industries [9]. Cross-industry and cross-sectoral collaboration within a community is required in order to exchange materials, energy, water and human resources [10], so the given heterogeneous capabilities and resources in the business environment must be taken into account [5].

Fig. 1 shows one possible approach for an Eco-Industrial Park (EIP) evolution following a continuous improvement process, the principle of PDCA (Plan-Do-Check-Act), whereat this study focuses on the first two steps: system analysis and the identification of IS opportunities. Noteworthy, the process borders of the five illustrated steps are not sharp, but partly overlapping and intertwining, especially step 2 and 3.

The process of retrofitting an existing Industrial Park (IP) and thus identifying potential industrial symbioses (IS) can be conducted by various quantitative methods. First of all, the actual state of the system of the IP and its economic actors needs to be analyzed. As a first starting point, a list of the companies involved can be assembled, in order to identify further (potential) linkages between the occupants such as same supplier and waste disposal companies. Then appropriate methods of constructing such connections can be defined and/or new elements that can be established into the park such as additional block heat and power stations, renewable energy sources and wastewater treatment plants can be detected [11]. For example, [10] firstly determined an initial synergy network of the participating companies in an IP, in order to identify common suppliers. They modelled an IS network where the entities involved as suppliers, receivers and processes were conceived in analogy as a supply chain. Therefore, they developed an industrial symbiosis supply chain model (ISSC), in order to point out IS opportunities that the companies may have in comparison to a traditional supply chain [10].

relationships in production or business networks. [52] analyzed the Kalundborg Industrial Symbiosis in Denmark using SNA to gain insights of the resilience of an IS network, suggesting design strategies for resilient and sustainable industrial symbiotic networks such as increased diversity, redundancy, and multi-functionality to ensure flexibility and plasticity.

The following three methods are mainly based on the principles of Output-Input and Supply-Demand

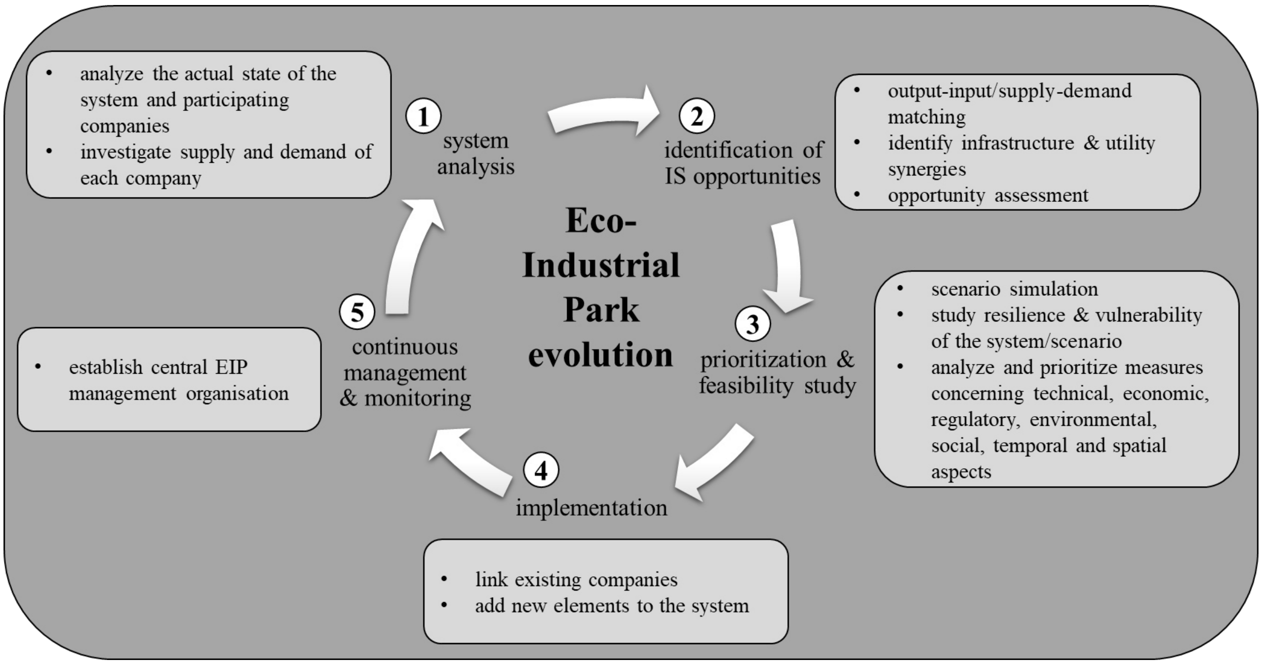


**Fig. 1: One possible approach for an Eco-Industrial Park (EIP) evolution.**

In this study, four basic methods were identified that have been used in case studies to reveal IS opportunities and network expansion: Social Network Analysis (SNA), Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA) and Life Cycle Assessment (LCA).

**SNA** investigates social structures of networks and characterizes elements within the network in terms of nodes (e.g. individual actors, companies, people) and the connecting ties or links (relationships or interactions) [11,24,44,45]. SNA can provide insights for understanding the social aspects of such a network system and how (social) business relationships drive the exchanges of materials, energy and information [45]. For instance, [44] investigated the relationships among industrial organizations in an IP in Puerto Rico, including interpersonal and organizational relationships, trust and the associated relationships within the IS network. [45] used SNA in an empirical study of IS that addressed trust

Matchings of the entities involved. So by analyzing each supply-demand and output-input (e.g. human and material resources, utilities and (infra-)structure) of each company, possible IS potentials can be identified.

**MFA** quantifies the flows and stocks of materials and energy of the system under consideration in physical units [11,24]. For instance, [51] conducted a multiyear investigation of industrial sites in Puerto Rico between 2001 and 2007. They used MFA to develop IS scenarios focused on utility sharing, joint service provision and by-product exchanges, which were evaluated by technical, economic and environmental criteria afterwards. [50] applied MFA to an industrial area in South India to analyze the recovery, reuse and recycling of industrial residuals and to identify existing symbiotic connections within this area. [12] conceptualized a web-based ICT solution that enables cross-organizational access and information exchange in order to reveal IS opportunities. It supports the planning, development and management of an IP from an environmental and sustainability perspective with the method of MFA.

**LCA** quantifies the flows and stocks of materials and energy of the system under consideration and assesses the associated environmental impacts [11,24]. [13] analyzed a Finnish Forest Industry Complex around a pulp and paper mill using LCA, in order to identify inter alia potential additional connections of the occupants. While [53] investigated IS in the biofuel industry in Sweden using LCA to identify synergies and quantify the environmental performance of the firms in the IS network. This method also offered an approach to distribute impacts and credits for the IS exchanges among the entities involved and to assess the benefits of the IS network [53]. It was proposed that this may also have implications for future development of taxes, incentives and subsidies [53].

**MFCA** traces and quantifies the flows and stocks of materials and energy of the system under consideration in physical and monetary units. Especially the material losses, non-product and waste flows are evaluated. Consequently, waste flows are attributed an economic value which incentivizes the optimization the company´s processes as well as the use of resources [32]. Previous research has shown that remarkable environmental and economic benefits have been achieved by implementing and applying MFCA on the level of an individual company [46,47]. The costs associated with wasted materials can accumulate to 40-70% for individual companies [48,49]. [14] conducted a case study in Indonesia by using a complementary approach of MFA, LCA and MFCA, proposing a preliminary new system design of cement production.

### 3.2. IT-supported Industrial Symbiosis Tools, learnings and implications

17 ICT applications for Industrial Symbiosis (IS) were investigated by [15], whereat most of them are either inoperative or not publicly available. Three of them specifically addressed the geographical scale of an industrial park (IP): *Knowledge-Based Decision Support System* (KBDSS), which is not available, *Designing Industrial Ecosystems Toolkit (DIET)*, which is reportedly unusable and *Industrial Ecology Planning Tool (IEPT)*, which requires ArcView GIS and its source code is available [15]. The geographical scope of the other tools considered the city/state, region and nation [15].

Nevertheless, based on the conducted literature analysis, there were three publicly available ICT solutions found which explicitly facilitates IS identification. [9] found several more IT tools, but note that they included various concepts such as social network platforms and IS knowledge repositories and region identification systems for IS. This study focuses on the actual IS identification among economic actors.

The Italian agency for new technologies, energy and sustainable economic development (ENEA) developed a *GIS-based web platform* to identify IS opportunities on a regional scale by Input-Output Matching [16]. The most significant non-technical barriers for IS implementation were the regulatory and control systems, including environmental regulation, lack of cooperation and trust between industries, economic barriers, as well as lack of information sharing [16].

*The Resource eXchange Platform (TRXP)* is a resource exchange web-platform that facilitates Industrial Symbiosis (IS) by building a network of organizations in Europe to enable the reuse of industrial streams of ICT equipment [17]. [17] showed that the tool was technically feasible, but nevertheless economic validity and regulatory constraints were considered to be challenging.

*eSymbiosis* is a web-based platform, providing knowledge-based services that reveal IS opportunities by matching supply and demand of resources in Europe [18]. It is built as an e-marketplace to trade the residual and by-product flows in a business-to-business (B2B) domain [18].

The studies of [9,15] conclude that most of the systems have not been designed for commercial purposes but predominantly concentrated more on the functionality and technical opportunities rather than connecting economic actors by building human and business relationships which is considered to be one of the main reasons for their failure. So they pointed out general strengths such as the identification of possible physical exchange processes in the sense of closing material flows, but they identified a lack of sociability, for example the inputs and outputs were connected well but the responsible people have been neglected [9,15].

Potentials for improvement for developing ICT tools for IS should address the social aspects such as better relationship management, initiation processes, the formation of trustworthy relationships between the economic actors participating in an IS and the facilitation of cooperation [9,15]. Additionally, many of the investigated tools presuppose advanced computer and programming skills and a comprehensive knowledge of the industrial organizations, so advancements of ICT tools for IS should address a better usability and sociability to shorten the duration of training and generate higher motivation for new users [15]. Further success criteria are the industry adoption of standardized (waste) taxonomy and the presence of a key number of organizations [9]. For example, the web-based waste exchange platform *WasteX* was developed for developing economies, but the system was cancelled due to a lack of industrial adoption [9,19].

Most of the investigated ICT tools for IS apply the method of output-input matching of various resource flows among industrial organizations, but do not provide decision support such as advanced analysis regarding economic viability of different IS opportunities, which is an essential challenge in enabling and facilitating IS [20,21].

[20] developed a system architecture of an IS collaboration platform by using the by-product exchange network (BEN) model. The BEN model is based on an agent-based modelling approach (ABM) [20]. ABM is a class of computational models for simulating various scenarios of the outcome of the actions and interactions of autonomous agents within a system (both individual or collective entities such as organizations or groups) [11,23]. They used a case study of food waste in Singapore, they applied the model as a decision support tool for companies to evaluate the economic viability of IS [20]. So in the model, entities such as plants or facilities in the IS network are represented by agents that are programmed based on rules to actively consume and/or produce resources, while resources are represented by agents that passively change their states such as quantities and locations [20].

As there are first starting points and approaches to solve these issues gradually, the lessons learned and corresponding implications have been incorporated into a preliminary concept for an IT-supported IS tool, whereat the ABM approach was not included because the focal point of this study was on the system analysis and IS identification (see Fig. 1, step 1 & 2).

## 4. A preliminary concept for an IT-supported Industrial Symbiosis tool

Usually an Industrial Park (IP) is mainly characterized by small and medium-sized companies, hence it is considered that an overarching coordinating body or organizational unit plays an essential role to support various Industrial Symbiosis (IS) activities such as the implementation of supply-demand/output-input matches, logistics, capacity management [5,9,25].

Based on the conducted literature analysis, a preliminary concept for an IT-supported IS tool is presented in this study, which is currently in the phase of prototyping. The elements of IS identification and assessment are combined into an overall web-based platform (this can be extended to a mobile application with responsive design as well) in order to provide integrated extensive toolboxes. Additionally, it shall support the coordination and management, specifically to facilitate the retrofitting of an industrial park into an EIP by identifying IS potentials and initiate implementation processes.

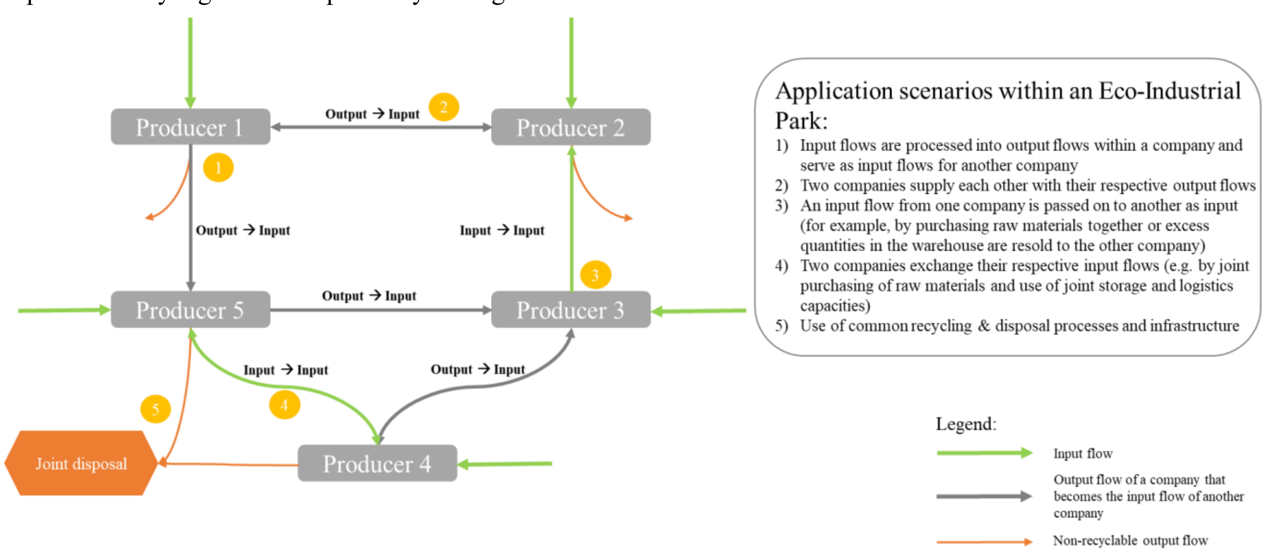


**Fig. 2. Application scenarios within an Eco-Industrial Park for the concept of the web-based Industrial Symbiosis tool.**

Fig. 2 shows several application scenarios included in the concept for the web-based IS tool. It goes beyond a simple output-input matching of the involved entities, it also considers the development of joint procurement, recycling and disposal processes and (infra-)structures.

The preliminary concept for an IT-supported IS tool comprises five modular functionalities: 1) analysis toolbox, 2) facilitated synergy identification (IS), 3) interactive marketplace, 4) communication and collaboration platform, 5) cross-company management (see Fig. 3).

which only shows the relevant input and output material and energy flows that lead into and leave the plant, whereby a deeper detailed level of process mapping does not take place [22]. However, this basic model is too abstract to identify weak points and optimization potentials, so that the operational processes have to be presented in more detail [22]. In addition to depth

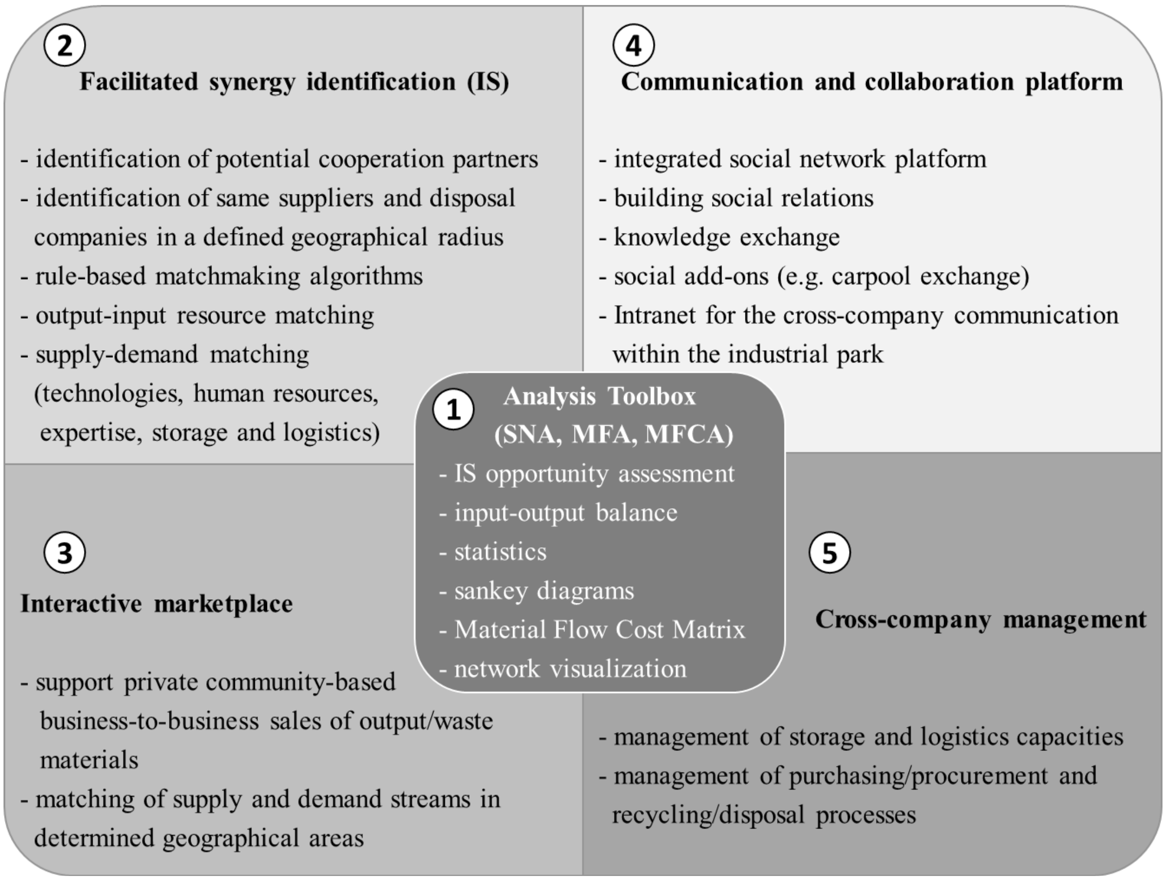


**Fig. 3. Preliminary concept for a web-based Industrial Symbiosis application.**

1) As an integrated component-based module, the flexible modelling of operational processes at the level of material and energy flows is to be analyzed and presented. Therefore, an *integrated analysis toolbox* with various evaluation methods (SNA, MFA, MFCA) is provided in the central core of the web application. In this case, the method of LCA can be optionally integrated, but requires a connection to a database such as GaBi or ecoinvent. For cost reasons, therefore, the LCA method is not included in the concept for the basic package. The simplest case of an energy and material flow model is the black box model of the plant, resolution, the modeling system also has to allow flexible resolution in width, so that the scope of the energy and material balance can also be flexibly expanded, for example, upstream (suppliers) [22] or downstream. As a basis for a simulation of planned measures, the material and energy flow model also enables the estimation and evaluation of alternative actions [22]. A flexible modeling system with the evaluation options mentioned (SNA, MFA, MFCA) thus serves as an instrument for decision support. A comprehensive dashboard with visualized results in form of inter alia sankey diagrams,

statistics and input-output balances shall be provided.

2) The *facilitated synergy identification* of IS opportunities is based on underlying rule-based match-making algorithms including output-input as well as supply-demand resources such as technologies, human resources, expertise, storage and logistics in order to enable the identification of potential cooperation partners in a defined geographical radius, for example to identify same suppliers and disposal companies or to match input-output tables, for example the reutilization of industrial organic waste to bioenergy [59].
3) The *interactive marketplace* shall support private community-based business-to-business sales of residual output, waste materials by matching the supply and demand streams in determined geographical areas, in which material and waste taxonomy will be one of the greatest challenges, especially the specification of material and waste properties, including material quality.
4) As [26] pointed out "coordination does not automatically mean cooperation", one component of the IS tool shall address social aspects in order to promote good personal relationships and the cultivation of cooperation [11,60].
   The *communication and collaboration platform* includes an integrated social network platform, enabling social relations, intensifying networking and trust building among the economic actors. Participating companies shall be able to exchange knowledge and experiences concerning the identification and implementation of IS opportunities.
   Social add-ons shall be incorporated as well, e.g. a carpool exchange for the industrial area. Furthermore, inter-company communication and coordination is supported, for example by organizing cross-company sports, benefit and other cultural events via an integrated "Social Media" area or by creating other interest groups.
5) In the module of *cross-company management*, potential capacities of storage and logistics shall be identified in order to utilize free capacities optimally. The procurement, recycling and disposal processes shall be managed efficiently by merging external services and (infra-) structure for joint usage and better purchasing and payment conditions, resulting in mutual cost reduction and higher revenues due to increased capacity utilization.

The usability and sociability shall be increased by providing customized data input masks, clear and easy-to-understand visualization of results and interactive communication possibilities via an integrated social media platform. Data confidentiality shall be tackled inter alia by a login system with specified access and permission rules.

Furthermore, an internal evaluation for the entire industrial site is possible for the monitoring and control of regional energy and material flow management and hence the expansion of synergetic cascade use, provided that a higher-level organizational unit has been established for the industrial park. The individual companies would have the choice of which data and information they would release to/share with the overarching organization unit of the industrial park and can nevertheless make full use of the evaluation options for their internal purposes. The IT-supported tool to be developed is intended to provide concrete recommendations for action and starting points to companies and thus offers valuable information for decision making to improve their economic, ecological and technical performances. Furthermore, it can improve cross-company and employee communication and the expansion of social networking, as well as increase employee awareness for sustainability issues, leading to a reduction of the ecological footprint through increased resource efficiency.

## 5. Discussion and concluding remarks

In emerging and developing economies, industrial parks can be transformed towards Eco-Industrial Parks (EIPs), generating significant benefits for the environment, economy and society, as [61] found out by investigating 33 examples of EIPs in 12 developing and emerging economies, including their policy context. The progressive field of Industrial Ecology (IE), providing various approaches, perspectives and methods such as Industrial Symbiosis (IS) to tackle (at least partly) the nowadays challenges, raises enormous opportunities to improve resource productivity and efficiency while reducing the environmental burden [62]. Emerging and developing countries can exploit the concepts and tools of IE to generate and detect chances to capture new opportunities for a sustainable industrialization and development, enabling a resilient economy [63].

Such an IT-supported IS tool could be considered as a small cogwheel in a complex large system, a point of contact and leverage point to contribute to the trajectory of sustainable development, facilitating the expansion and intensification of interconnectedness and intra- and inter-organizational collaboration. The focus of such IS tools should be the identification of potential cooperation partners. This can be done via initial output-input matchmakings, but manual data entry of individual residual material flows is too cost-intensive from an economic point of view. So this can be partly tackled by (semi-) automated data gathering via specific sensors during the production processes [54]. Furthermore, many researchers argue that incorporating environmental data sets can benefit the IS identification tool regarding the exploration and assessment of IS opportunities [9,16,35,36,37].

IS tools for industrial companies should be designed for a commercial market, where the initial identification of cooperation partners should be the main focus in order to enable long-term business relationships. The IS tool should therefore provide more transparency among market players and propose potential cooperation partners according to selectable criteria (e.g. geographical radius, material properties, material quality, purchase quantity, delivery period), bringing synergy partners together. This tool can serve for initiation and provide decision support, but the complex business-driven negotiations and agreements for a long-term business relationship can only be supported to a certain limit. This is accompanied by confidence building and enables the economic evaluation of a company with regard to possible opportunities and risks such as security of supply of resources, including possible (seasonal, temporal and qualitative) variability and fluctuations, medium to long-term agreements on price and quality.

This is the reason why an industrial park is a good and feasible starting point with promising long lasting impacts and business relationships due to the "community effect" of an industrial park. So the expansion of an IS network is predominantly based on the collaboration and synergistic opportunities revealed by geographical proximity of the involved entities [4]. Thus, the resilience and sustainability of industrial symbioses are supported by geographical proximity and the long-term cooperation of the economic actors. The long-term exchange of resources such as excess waste heat flows can only be achieved by establishing a common infrastructure (common heat pipes) or other types of synergies such as joint procurement and disposal, as well as utility sharing requires geographical proximity. Building exchange networks of resources may create vulnerabilities by a higher degree of interdependencies among the entities and their performances, which requires an increased level of trust [9,39]. Utility sharing can be a tempting starting point to enhance IS, but several case studies suggest that material (by-product) exchanges may be a better first starting point for existing industrial parks [9,39,40,41]. It is argued that material exchanges have less potential of adverse effects [9,40,41]. Additionally, having backup systems can increase the resilience of an IS network by introducing redundant or similar entities [9].

This kind of ICT solution can be promising, especially from the perspective of small and medium sized enterprises (SMEs), concerning cost-benefit relationship and a continuous improvement of their economic, environmental and technical performance. Especially SMEs can benefit from such an IS approach, by identifying common suppliers and waste-disposal and recycling companies via the method of SNA in order to establish joint processes of procurement of materials as well as waste management and reduce costs.

Another challenge to be met adequately and in a sophisticated manner is the economic factor, which is considered to be the primary motivation and main driving factors to change existing systems [27,28,29,30,60]. Investments are to be made to implement IS opportunities, hence costs will occur [11,60]. Therefore, the question of the distribution of costs and potential future savings among the economic actors will arise [11]. If this is not considered fairly distributed, they may not adopt the proposed IS opportunity [11]. So one major facilitator for the expansion of IS networks is a component of an IS tool that shows the economic viability to the participating organizations [20]. A data oriented approach would be advantageous for revealing new IS opportunities as well as for assessing the economic benefits, substantiating the IS viability [31]. Such approaches can be inter alia applied by the method of MFCA. From a business perspective, placing MFA and MFCA at the starting point with a boundary of a production system and then exploring potential IS connections among the entities, a useful "road map" can be pursued to assess and prioritize IS opportunities from an economic perspective. Additionally, the basis of analysis can be expanded inter alia with the method of LCA to value chains and finally all life cycle stages of a product or service as it reduces the starting barrier and increases the complexity and scope gradually [33]. So in fact, MFCA shares a similar information and data base with various methods such as MFA, LCA and Carbon Footprinting [34].

Further research should address the combination of IS identification and assessment with the method of MFCA, as previous research has been scarce on that special topic. Additionally, the environmental and economic performance of an entire industrial park could be assessed and controlled. This could be investigated more in detail by conducting several case studies, in which especially knowledge and insights of barriers, enablers, benefits, risks and challenges of IS identification and implementation is gathered. The following questions are an excerpt of a possible questionnaire for future research:

- What is the current state of knowledge of the economic actors in an industrial park concerning IS and its applied methods to reveal IS opportunities?
- What are the key factors and drivers associated with IS implementation and the expansion of IS networks?
- What are the barriers, vulnerabilities and challenges of IS adoption? And how to tackle them?
- What are the success criteria for retrofitting an EIP?
- What can an optimally utilized industrial symbiosis of a given area look like?
- What is the current status of the area under consideration?
- How to achieve the desired future EIP scenario from the present status?
- Where are first simple starting points and leverage points for an expansion of an IS network?
- How might stakeholders become meaningfully engaged in systems co-design, so as to shape the emergent technology-enabled ecosystem?

For inter-organizational collaboration teams virtual work environments are becoming more relevant, therefore approaches such as Collaboration Engineering (CE) can be effective for creating design patterns and deriving design guidelines for virtual collaboration processes [56]. To design such collaboration systems many interrelated issues of higher complexity and volume in a social-technical context have to be addressed adequately. Referring to [55,64], a Seven-Layers Model of Collaboration (SLMC) was developed for designers of collaboration support systems in the context of CE, which considers differing levels of abstraction and addressing different concepts, techniques and tools in each layer. According to [57], “the power of facilitated collaboration is also validated as helpful for trust development.” They made several implications, such as proposing a series of trust antecedents, a treatment design of a CE approach for trust improvement, and a new context application of CE [57].

With regard to enabling Industrial Symbiosis (IS), the great challenges lie in building trust and intensifying cooperation among economic actors [15], developing a healthy balance among all stakeholders´ interests [60], while maintaining data confidentiality, regulatory compliance and reducing potential organizational risks such as misuse of provided information [9]. More research is necessary to address such topics adequately, in order to remove or at least lower technical, economic, organizational and social barriers [38], increase the resilience of an emerging EIP and foster long lasting business relationships in the context of IS, enabling safe operating cooperation environments.

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## 5. Paper 2: Requirements Engineering for an Industrial Symbiosis Tool for Industrial Parks Covering System Analysis, Transformation Simulation and Goal Setting

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For better readability, better understanding and a logical structure of the research work, the original publications are inserted in each case.

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# Requirements Engineering for an Industrial Symbiosis Tool for Industrial Parks Covering System Analysis, Transformation Simulation and Goal Setting

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**Abstract:** Industrial Symbiosis (IS) is a collaborative cross-sectoral approach to connect the resource supply and demand of various industries in order to optimize the resource use through exchange of materials, energy, water and human resources across different companies, while generating ecological, technical, social and economic benefits. One of the main goals of IS is the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple utilization within industrial systems in order to increase resource productivity and efficiency, while reducing the environmental load. Many Information Communication Technology (ICT) tools have been developed to facilitate IS, but they predominantly focus on the as-is analysis of the IS system, and do not consider the development of a common desired target vision or corresponding possible future scenarios as well as conceivable transformation paths from the actual to the defined (sustainability) target state. This gap shall be addressed in this paper, presenting the software requirements engineering results for a holistic IT-supported IS tool covering system analysis, transformation simulation and goal-setting. This new approach goes beyond system analysis and includes the use of expert systems, system dynamics and Artificial Intelligence (AI) techniques, which turn the IT-supported IS tool to be developed into a comprehensive and holistic instrument with which future scenarios and transformation paths can be simulated.

**Keywords:** Industrial Symbiosis; Industrial Ecology; expert system; Artificial Intelligence; Machine Learning; Agent-Based Modelling; system dynamics; resource efficiency; resource productivity

## 1. Introduction

Current global challenges such as climate change, increasing freshwater consumption, chemical pollution (Rockström et al. 2009) and limited resource availability have triggered social, governmental and economic activities to reduce the burden to ecosystem functioning and services to human societies. One of the application concepts in industrial contexts is Industrial Symbiosis (IS), which takes an emerging priority on the European Union (EU) policy agenda (EEA 2016) and is considered to be a key enabling factor for resource efficiency and circularity.

IS is a collaborative cross-sectoral approach to connect the resource supply and demand of various industries in order to optimize the resource use through exchange of materials, energy, water and human resources across different companies, while generating ecological, technical, social and economic benefits (Ehrenfeld and Gertler 1997; Chertow 2004; Van Berkel et al. 2009; Sokka et al. 2010; Herczeg et al. 2016; Ruiz-Puente and Bayona 2017; Chertow et al. 2019; Doménech et al. 2019). One of the main goals of IS is the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple utilization within industrial systems in order to increase resource productivity and efficiency, while reducing the environmental load.

The holistic view along the entire life cycle opens up various points of contact and leverage points for resource circularity opportunities and to improve the overall sustainability impact. Figure 1 shows four mechanisms as Life Cycle Material Reflows:

a) recycling reflow from the end of life phase back to the (raw) material processing stage,
b) remanufacturing reflow either from the end of life phase or from the consumption/usage step back to the manufacturing phase,
c) reusing reflow from the end of life stage back to the usage phase,
d) and the extended/internal cascading loops in IS systems in the manufacturing phase in form of water, material and energy networks, networks of shared utilities and infrastructure (incl. storage capacity and logistics) and networks of joint disposal and procurement processes. This is a further point of contact for increasing resource productivity/efficiency and reducing consumption of primary resources, while mitigating/reducing negative environmental burden and economic costs.

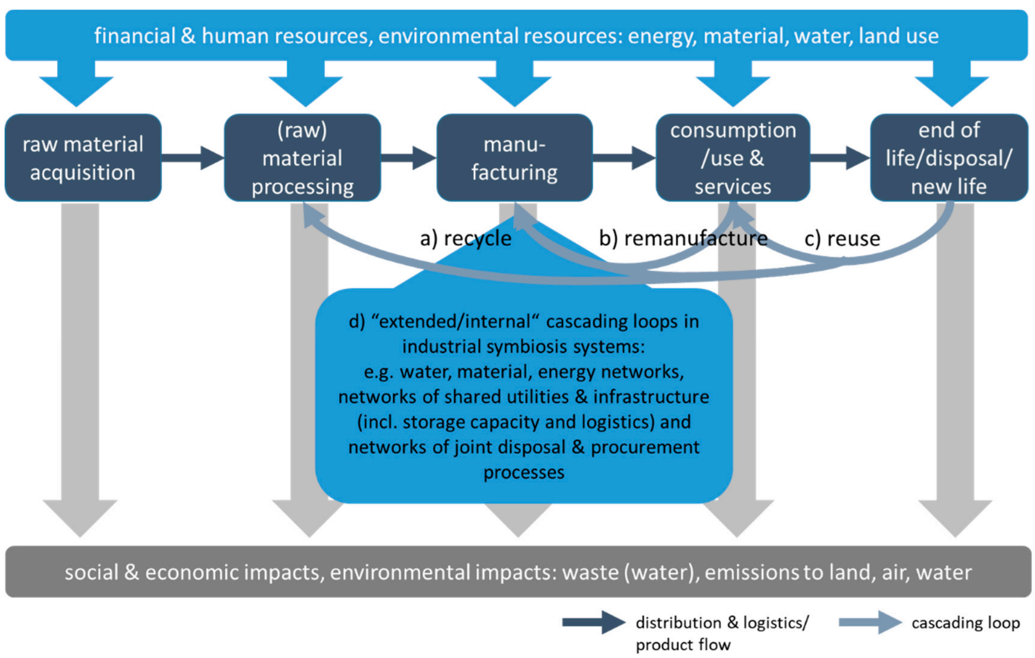


**Figure 1.** Life Cycle Material Reflows with Industrial Symbiosis as extended/internal cascading loop in the manufacturing phase.

Close geographic proximity is considered to be a facilitating factor for IS systems (Wallner 1999; Chertow 2004; Sterr and Ott 2004; Hewes and Lyons 2008; UNIDO 2016), that is why this work focuses on industrial agglomerations and industrial parks (IPs) as a starting context/geographical system boundary for IS. IPs could or should be seen as entire eco(sub-)systems (Côté and Hall 1995), which are embedded in the overarching natural ecosystem (Chertow 2008). According to Erkman (2001), ecologically oriented IPs consider technologies, process economics, the inter-relationships of businesses, financing, overall governmental policy, and the entire spectrum of issues that are involved in the management of commercial enterprises as equally important as environmental protection and optimizing the use of resources. According to Frosch and Gallopoulos (1989), they have three main principles: 1) the minimization of consumed energy, 2) the (re-)use of industrial waste, 3) the development of a resilient system.

Especially environmental regulations and laws are considered to be triggering and pushing forces for companies to engage in an IS system (Bacudio et al. 2016; Ji et al. 2020), beside the motivation of economic advantages. Among others, hindering factors are the lack of awareness of IS concepts (Sakr et al. 2011; Bacudio et al. 2016; Ji et al. 2020), lack of local IS possibilities, lack of information sharing among locators (Sakr et al. 2011; Bacudio et al. 2016), lack of an institutional support for integration, coordination and communication, lack of technology and infrastructure readiness (Bacudio et al. 2016) and difficulties in reaching agreements (Ji et al. 2020). The identified barriers of IS implementation has driven the current research work, which aims to tackle these aspects and facilitate the exploitation of IS to be used as a lever for a sustainable industrial development. Therefore, information exchange is crucial to identify IS business matches and potentials (Heeres et al. 2004; Ismail 2014). So, the inter- and cross-company information flows can be enabled by an information platform (Sakr et al. 2011; Isenmann 2013; Song et al. 2018). One of the essential technology-enabled factors is the establishment of an information platform, which provides an integrated analysis tool for the IP itself in order to add the functions of performance monitoring, social modules supporting trust and community building, and systematic approaches to identify possible IS activities and to evaluate them from an economic, social and ecological perspective (Lütje et al. 2018; Lütje et al. 2019a). Many Information Communication Technology (ICT) tools have been developed to facilitate IS, but they predominantly focus on the as-is analysis of the IS system (Grant et al. 2010; Maqbool et al. 2019). The main focus is on the identification of possible IS measures and (the management of) material and energy exchanges by output-input matching of various resource flows among companies, functionality and technical opportunities (Grant et al. 2010). Furthermore, decision support such as advanced analysis regarding economic viability of different IS activities (Raabe et al. 2017) and ecological impacts (reduction) are not provided. Additionally, the development of a common desired target vision for an IP or corresponding possible future scenarios as well as conceivable transformation paths from the actual state to the desired target vision are not taken into account. This gap shall be addressed in this paper, presenting the requirements engineering results for a conceptual IT-supported IS tool. This new approach goes beyond as-is and system analysis and includes the use of system dynamics and Artificial Intelligence (AI) techniques, which turn the IT-supported IS tool to be developed into a comprehensive and holistic instrument with which future scenarios and transformation paths can be simulated.

The following exemplary tools approach the dynamic effects and impacts of possible IS activities. Raabe et al. (2017) developed an IS collaboration platform, using a by-product exchange network (BEN) model based on an agent-based modelling approach (ABM). Applying the model to a case study of food waste in Singapore, it provided decision support for companies to evaluate the economic viability of IS (Raabe et al. 2017). Companies in the IS network are embodied by virtual agents. Each agent is programmed based on rules to actively consume and/or produce resources, while resources are represented by agents that passively change their states such as quantities and locations (Raabe et al. 2017). Yazdanpanah et al. (2018) studied IS networks with coordinated game theory and normative multi-agent systems in order to investigate fair and stable benefit allocation among IS entities. Yazan and Fraccascia (2019) proposed an IS model, enabling the exploration of "the space of cooperation, defined as the operationally favourable conditions to operate IS in an economically win-win manner". Therefore, they developed an IS decision-support tool which is based on an enterprise input-output model and provides a cost-benefit analysis (Yazan and Fraccascia 2019). An agent-based simulation was incorporated to present the share allocation of the total economic benefits resulting from IS activities (Yazan and Fraccascia 2019). Lütje et al. (2019b) proposed a first framework concept for a combinatorial approach of Agent-Based Modelling (ABM) and the Artificial Intelligence (AI) technique of Reinforcement Learning (which belongs to the sub-field of Machine Learning (ML)) for exploring the system dynamics of IS. So, the agents can take note of rewards received by specific actions and record it, in order to adapt the model and accelerate the learning phase for better solution finding. This hybrid-approach opens up the simulation of scenarios with optimally utilized IS systems in terms of system adaptability and resilience (Lütje et al. 2019b).

However, the evaluation, simulation, planning, implementation and operation of IS activities need to be carefully considered beforehand, as the (long-term) functioning/success of IS is highly context-depend (e.g., local circumstances of resource availability/scarcity, political, technological, socio-cultural and organizational aspects). In some contextual constellations IS may not be the only or optimal approach to solve resource efficiency and productivity problems (Holgado et al. 2016), as it may shift the issue out of the IS scope, and then may occur elsewhere. Blinkered thinking should therefore be avoided and socio-ecological-economic effects of IS measures should also be taken into account beyond the IS scope in order to assess the overall sustainability effectiveness.

## 2. Results

### *2.1. Applied Methods in Industrial Symbiosis Systems*

Traditionally, IS networks have been divided up into three main categories of exchange types: water, power (including heat) and materials (Kastner et al. 2015). The process of identifying IS opportunities can be conducted by various quantitative methods. Table 1 shows the methods applied to IS systems and their application context of the investigated case studies (see full list in Appendix A). It is noteworthy that there are various more methods applicable to IS systems; the ones listed here capture exclusively the results of the conducted cross-case analysis. Particular attention was paid to ensure that the methods selected were suitable for the application context of the IT tool to be developed and the usability of companies. In this study, the methods of Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Social Network Analysis (SNA) were detected as the most applied methods in the IS context to reveal IS opportunities and analyze the actual state of an IS system. Other researchers confirm these findings very close to congruent (Li et al. 2017; Kastner et al. 2015; Huang et al. 2019): the most widely applications are MFA (Geng et al. 2012; Sendra et al. 2007; Yong et al. 2009), LCA (Sokka et al. 2010; Sokka et al. 2011), and environmental indicators (Kurup and Stehlik 2009; Pakarinen et al. 2010; Zhu et al. 2010). Which methods are considered for which purpose and for which context? This needs to be differentiated when applying various methods for the IS identification, IS performance measurement and the investigation of existing IS systems concerning inter alia the structure and morphology, etc.

In the following, a selection of diverse case studies is described to briefly demonstrate the various application possibilities and contexts of the presented methods. For instance, Bain et al. (2010) conducted a case study on an industrial site in South India, using MFA to analyze the recovery, reuse and recycling of industrial residuals and to match potential IS connections among companies. Chertow et al. (2008) applied MFA in a multiyear investigation (2001-2007) of industrial areas in Puerto Rico, in order to develop IS scenarios dedicated to utility sharing, joint service provision and by-product exchanges, which were evaluated by technical, economic and environmental criteria afterwards. LCA was used by Sokka et al. (2010) who investigated a Finnish Forest Industry Complex around a pulp and paper mill, in order to identify inter alia potential IS connections. Martin (2013) explored IS in the biofuel industry in Sweden to identify IS potentials and quantify the environmental impacts of the IS network with LCA. This method also revealed an approach to allocate impacts and credits for IS exchanges among the occupants and to assess the environmental benefits of the IS network (Martin 2013). Ulhasanah and Goto (2012) applied MFA, LCA and MFCA in a cement production case study in Indonesia, in order to identify IS opportunities and evaluate them from physical, environmental and economic perspectives.

So, in the IS context, MFA, MFCA and LCA are mainly based on the principles of Output-Input and Supply-Demand Matchings of the entities involved. By analyzing and matching each supply-demand and output-input (e.g., human and material resources, utilities and (infra-)structure) of each company, possible IS connections can be revealed. From the methodological perspective, MFA is the first basis to map physical resource flows (material, water, energy) and respective processes. LCA and MFCA can then be set up on this foundation to illuminate the environmental impacts/performance (LCA) and/or the economic performance of, particularly, processes, resource and waste flows (MFCA).

**Table 1.** Overview of methods for the identification and investigation of IS systems and their application context.

| Method | Description | Application Context | References |
|---|---|---|---|
| Material Flow Analysis (MFA) | Quantifies the flows and stocks of materials and energy of the system under consideration in physical units (e.g., kg), distinguishing between input and output streams of the respective processes | Applicable to material and energy flows, crossing exchange type boundaries (water, power, materials), first starting point to visualize the (production) system with its respective input and output flows and screen first possible IS matchings | Chertow et al. 2008; Park et al. 2008; Yang and Feng 2008; Zhu et al. 2008; Van Berkel et al. 2009; Yuan and Shi 2009; Bain et al. 2010; Ulhasanah and Goto 2012; Sun et al. 2016; Li et al. 2017; Taddeo et al. 2017; Mauthoor 2017; Morales et al. 2019 |
| Substance Flow Analysis (SFA) | Quantifies and traces the flows and stocks of one specific substance/chemical or a group of substances within the system under consideration | Detailed investigation to determine the flows and stocks of one specific substance, suitable, if further clues have already been identified in the system/context, for disclosing IS possibilities for a particular substance. | Zhang et al. 2013a; Wen et al. 2015 |
| Material Flow Cost Accounting (MFCA) | Traces and quantifies the flows and stocks of materials and energy of the system under consideration in physical and monetary units, especially the material losses, non-/by-products and waste flows are evaluated (standardized to ISO 4051) | MFCA is based on the method of MFA, additionally all input and output flows are attributed an economic value, especially the material losses/waste flows, which incentivizes the optimization of processes as well as the use of resources and provides a better decision-making basis regarding economic viability and prioritization of IS measures | Viere et al. 2011; Ulhasanah and Goto 2012; Lütje et al. 2018; Lütje et al. 2019 |
| Life Cycle Assessment (LCA) | Quantifies the flows and stocks of materials and energy of the system under consideration and assesses the associated environmental impacts, such as global warming and eutrophication potential | LCA is based on the method of MFA, applicable to material, water and energy flows, considers all exchange type boundaries throughout an entire product life cycle (from raw material extraction, production, distribution/retail, to usage and disposal), assesses the environmental impacts of products and services. | Sokka et al. 2010; Ulhasanah and Goto 2012; Marinos-Kouris and Mourtsiadis 2013; Sacchi and Ramsheva 2017; Marconi et al. 2018; Martin and Harris 2018; Chertow et al. 2019 |

| | | | |
|---|---|---|---|
| | (standardized to ISO 14040) | | |
| Emergy Analysis | Emergy is an expression of all the energy consumed in direct and indirect transformations in the processes to generate a product or service. Therefore, emergy analysis converts the thermodynamic basis of all forms of energy, resources and human services into equivalents of a single form of energy(usually solar emjoules). | Emergy is a more comprehensive and adequate way to value ecosystem goods and services, as they convey the past work performed by the environment, economy and society and does not consider only the amount of available energy that is used in the present to produce a good or service. | Geng et al. 2014; Sun et al. 2016; Liu et al. 2018 |
| Social Network Analysis (SNA) | Investigates social structures of networks and characterizes elements within the network in terms of nodes (e.g., individual actors, companies, people) and the connecting tie or links (relationships or interactions). | SNA analyzes the characteristics, power quantification and structure of the IS network and can provide insights for understanding the social aspects of an IS system and how (social) business relationships drive the exchanges of materials, energy and information | Ashton 2008; Doménech and Davies 2009; Doménech and Davies 2011; Zhang et al. 2013a; Chopra and Khanna 2014; Song et al. 2016 |
| Agent-Based Modelling(ABM) | ABM is a class of computational models for simulating various scenarios of the outcome of the actions and interactions of autonomous agents within a system (both individual or collective (both individual or collective entities such as originations or groups) | In an ABM model, entities such as plants or facilities in the IS network are represented by agents that are programmed based on rules to actively consume and/or produce resources, while resources are represented by agents that passively change their states such as quantities and locations, suitable for simulating and modelling various IS scenarios and considering potential effects regarding vulnerability and resilience of the IS system. | Axtell et al. 2001; Raabe et al. 2017; Yazdanpanah et al. 2018; Yazan and Fraccascia 2019 |

The research methods on IS have expanded from focusing on material flows, environmental and economic benefits to broadening it to social aspects as collaboration and the relationships among the IS entities can profoundly determine the effectiveness and efficiency of the entire IS system. With the method of SNA, the structure of IS systems and the (power) relationships of the entities involved can be investigated. For instance, Song et al. (2016) analyzed the Gujiao eco-industrial park in China and found out that SNA reveals IS potentials to develop more synergy linkages, identifying key/anchor actors in the network and their relation/context to exchanges of material, energy and (waste) water. Ashton (2008) addressed interpersonal and organizational relationships, trust and the associated relationships within the IS network in an IP in Puerto Rico with SNA. Chopra and Khanna (2014) used SNA to study the Kalundborg Industrial Symbiosis in Denmark regarding the resilience of an IS network, suggesting design strategies for resilient and sustainable IS systems such as increased diversity, redundancy, and multi-functionality to ensure flexibility and plasticity.

All investigated case studies have in common, that they were used to analyze and describe the actual state of the IS system and to derive various IS measures, but no one mentioned that it was done in a targeted manner, so no explicit goals were defined when identifying and implementing IS opportunities.

### *2.2. Industrial Symbiosis Material Exchanges and Activities*

The conducted cross-case analysis revealed several points of contact for a company to investigate systematically potential IS activities. In the following, a systematized overview was abstracted and exemplary cases are shown:

1. **Non-material exchanges**: sharing of knowledge/expertise, utilities/infrastructure, management of joint procurement and disposal/recycling processes. Mirata and Emtairah (2005) studied the Landskrona industrial symbiosis programme (LISP) in Sweden and found out that inter-organizational collaboration was not only important in implementing identified IS solutions, but also contributed to mutual learning in various forms. LISP actors were engaged not only in material exchanges, as this is more common in IS networks, but rather in cooperation on non-material synergies such as management routines, new business arrangements, collective bargaining, and envisioning joint goals towards sustainable development (Mirata and Emtairah 2005).

   Beside non-material exchanges, there are physical exchanges of water, energy and materials.

2. **Input-related material and energy resources:**

   **2.1. Secondary raw/substitute materials:** Liwarska-Bizukojc et al. (2009) presented an Austrian IS example, in which the manufacturer of cellulose insulation collected wastepaper from onsite companies to re-process and re-utilized it as secondary raw material.

   **2.2. Energy**

   **2.2.1. (process) heat/cold (process):** Martin et al. (2011) studied the Händelö IS in Sweden, where the municipal wastes, process waste and biomass from local forestry industries feed a combined heat and power unit (CHP). Heat is injected in the district heating network, electricity to the grid, and steam to the nearby ethanol production plant, which also produces by-products that are forwarded to the biogas plant (Martin et al. 2011).

   **2.2.2. electricity:** Jyrki (2009) investigated an IS system of copper and nickel flash smelters, a nickel chemical producer, an energy producer, a hydrogen plant, a sulphuric acid plant and the town of Harjavalta in Finland, which have established symbiotic exchanges of energy cascading and material flows.

   **2.3. (process) water:** Shi et al. (2010) showed the water and energy cascading system of an IS network in China, which included additional waste and wastewater recovery and by-product exchanges.

3. **Output-related emissions:**

   **3.1. Waste heat/steam:** can be forwarded to other companies (Mirata 2004; Pakarinen et al. 2010; Yu et al. 2015; Earley 2015). Li (2011) presented an IS complex in China, comprising power generation, desalinization, sea salt production, brick production and a chemical plant. The

IS network predominantly covers waste heat recovery and by-product exchanges such as the material utilization of coal ashes for brick production (Li, 2011).

3.2. **Gaseous waste/aerosols:** Melanen et al. (2008) studied an IS network in Finland, which has been established around a large pulp and paper mill. Among other things, the CO2 emissions are passed on to a calcium carbonate plant as a secondary raw material. Aerosol waste streams such as fly ash can be used as cement additive (Dong et al. 2013; Golev et al. 2014; Cui et al. 2018) or soil additive (Korhonen et al. 2005; Notarnicola et al. 2016; Bain et al. 2010).

**4. Output-related waste:**

**4.1. Solid waste/residuals:** Costa and Ferrão (2010) explored an IS system in Portugal, which is mainly characterized by the economic sectors of waste management and recovering industry (inter alia aluminium slag, plastic, battery recycler). Organic residual (solid) waste can be converted to animal/fish feeding (material utilization) (Chertow 2007; Alkaya et al. 2014), or where health and hygiene reasons need to be considered, can be processed into biogas and biofuel (energetic utilization) (Alkaya et al. 2014). The digestate of a biogas plant can be reused as fertilizer (Martin 2013; Alkaya et al. 2014).

**4.2. Liquid waste:**

**4.2.1. (waste/process) water:** Wastewater from a company that processes food such as olives, cereals, fruit and vegetables can be further used for the fertilized irrigation of agricultural land (Chertow et al. 2008; Notarnicola et al. 2016) or further processed into a fertilizer product.

**4.2.2. Sludge/mud:** the Guitang Group in China solved a disposal problem by using their sludge as the calcium carbonate feedstock to a new cement plant, while reducing residual and waste flows (Zhu et al. 2007).

In order to provide better knowledge diffusion and experience transfer, practical cases of IS and concrete material and energy exchange measures found in literature should be gathered in an IS (relational) database, creating a catalogue of IS material and energy exchanges and IS activities. The development of such a database should contain information of concrete IS measures and experiences, broken down by industrial sector, which company type/branch cooperates with which company type/branch and recording each input flows by type of energy and materials (raw materials, consumables and supplies) and output flows by product, by-product, residual and waste flows, on the one hand, and their corresponding application context and processing possibilities for output flows, on the other hand, in order to facilitate the identification of (further) IS opportunities. The existing (scientific) literature and the corresponding knowledge about IS systems already provides a sufficient basis for the development of extended IS cascade systems as generalizable templates/basic blueprints, which can be deposited in data/knowledge bases in order to facilitate and outline further IS exchanges and connections. With such a knowledge/insight base, concrete recommendations for action can be derived for specific IS activities and mapped/applied to the existing area under consideration. For example, there are concrete recommendations for utilization in which it is specified which output stream can be used as which input stream of another company, facilitating input-output/supply-demand matchings and suggestions. This can then be used in recommendation components of the presented concept for an IT-supported IS tools.

### *2.4. Requirements Engineering Results for the IT-supported Industrial Symbiosis Tool*

All the collected information based on the conducted cross-case analysis were incorporated into a systematized Requirements Engineering (RE) scheme (see Figure 2) in order to envision a concept for a holistic IT-supported IS tool for the evolution of Industrial Symbiosis (IS) in Industrial Parks (IPs). For this purpose, modular solution approaches were designed that address all three types of knowledge (system, transformative and normative). The concept includes elements of system analysis, information and collaboration platform, goal setting, the IS identification and assessment as well as the simulation of transformation pathways, which are combined into an overall web-based platform.

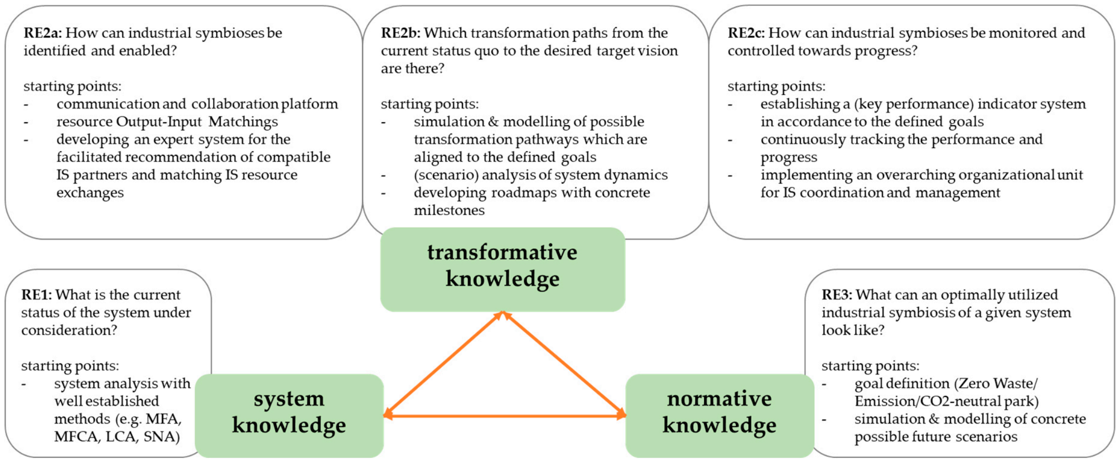


**Figure 2.** Systematized Requirements Engineering (RE) scheme.

The web application to be developed is based on the analysis toolbox (see Table 2, SK1.0), in which every company can store its information and data with specific access rights. The introduced methods in this paper such as MFA, SNA, LCA and MFCA are means to describe the actual state of the system under consideration, which already can reveal IS opportunities. The visualization of the results is carried out by means of input-output balance sheets, statistical graphs, indicators, Sankey diagrams[1], material flow cost matrices[2] and sociograms[3]. From a business perspective, a successive and gradual approach is suggested to reduce the starting barrier by placing MFA and SNA at the starting point for exploring potential IS connections among the entities, then the scope of the investigation can be narrowed and specifically targeted towards a more detailed level. Additionally, to the Input-Output and Supply-Demand Matchings, with the method of SNA, same suppliers and recycling/disposal companies can be detected, so that the IS network can be intensified (Lütje et al. 2019a). Depending on what objectives have been defined, appropriate methods can then be applied showing the ecological and/or economic perspective in more detail in order to assess and prioritize IS opportunities. So, the basis of analysis can be expanded inter alia with the method of MFCA (economic focus) or LCA (environmental focus) and, hence, increasing the complexity and scope gradually.

**Table 2.** Detailed Requirements Engineering Overview.

| Nr. | System Knowledge (SK) | Remarks |
|---|---|---|
| **SK1.0** | **Analysis Toolbox** | |
| SK1.1 | Energy and Material Flow Analysis (MFA) | System analysis of physical input-output resource flows in order to identify compatible IS resource exchanges and increase resource productivity and efficiency by reducing primary resource consumption. |
| SK1.2 | Material Flow Cost Accounting (MFCA) | Economic evaluation of resource flows, especially waste flows, in order to generate cost savings and incentivize/prioritize IS measures. |

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1 A Sankey diagram is a graphic representation of physical quantity flows of the respective resources with arrows proportional to the quantity.

2 A material flow cost matrix shows the process-specific material flow cost allocation of a company in accordance to the four major cost items: material, energy, system and waste management costs.

3 A sociogram is a graphic representation of the connections and relationships among group members.

| | | |
|---|---|---|
| SK1.3 | Life Cycle Assessment (LCA) | Environmental evaluation (e.g., global warming potential, eutrophication potential, ozone depletion potential) in order to reduce environmental impacts and drive/prioritize IS measures. |
| SK1.4 | Social Network Analysis (SNA) | Investigation of the as-is structure/composition of participating companies and their (power) relationships in order to intensify network connections, identify same suppliers and disposal companies and to evaluate the system resilience of IS activities. |
| | | **Transformative Knowledge (TK)** |
| **TK1.0** | **Information exchange** | |
| TK1.1 | Integrated social network platform with social add-ons | Inter-company communication, nurturing social relationships, trust and community building shall be supported. |
| TK1.2 | Knowledge exchange | Enabling knowledge transfer between participating companies (e.g., experienced companies in auditing/certification processes can share their knowledge with unexperienced companies which plan certain audits and certifications). |
| TK1.3 | Cross-company IS management | Enabling joint management of e.g., storage and logistics capacities, joint procurement and recycling/disposal processes. |
| **TK2.0** | | **Facilitated Synergy Identification** |
| TK2.1 | Resource Output-Input Matchings | Matching of actively supplied and demanded resource output-input flows of participating companies. |
| TK2.2 | Supply-Demand Matchings | Referring to actively supplied and demanded technologies, human resources, expertise, storage and logistics capacities. |
| TK2.3 | Integrated expert system | For the facilitated recommendation of compatible IS partners, matching IS resource exchanges and additional IS activities in order to exhaust further IS potentials. |
| **TK3.0** | | **Simulation and Modelling** |
| TK3.1 | simulation and modelling of possible transformation pathways | which are aligned to defined goals (e.g., via Agent-Based Modelling and/or other methods of (scenario) analysis of system dynamics). |
| TK3.2 | roadmaps | Developing roadmaps with concrete milestones and measures. |
| TK3.3 | (key performance) indicator system | Continuously tracking the performance and progress towards the defined goals. |
| **TK4.0** | | **IS administration and management** |
| TK4.1 | overarching organizational unit | For IS coordination and management with administrator function of the IT-supported IS tool. |
| | | **Normative Knowledge (NK)** |
| **NK1.0** | **Desired future visions** | |
| NK1.1 | Goal setting | Participating companies are encouraged to collaboratively define quantifiable (sustainability) goals for the IS network (e.g., zero waste park, zero emission park, CO2-neutral park). |
| NK1.2 | Possible future scenarios | Simulation and modelling of concrete possible future scenarios that allow the full range of IS potential to be exploited. |

As Boons and Baas (1997) pointed out "coordination does not automatically mean cooperation"; the second component of the IS tool addresses social aspects (Table 2, TK1.1) in order to foster good personal and business relationships and the cultivation of cooperation (Sakr et al. 2011). The communication and collaboration platform comprises an integrated social network platform, enabling social relations, intensifying networking and trust building among the entities. Social add-ons for the industrial area shall support the inter-company communication and trust building, for example, by organizing cross-company sports, benefit and other cultural events via an integrated "Social Media" area or by creating other interest groups such as a carpool exchange for the local employees. Especially the exchange of information shall be promoted, so that knowledge and experience transfer and diffusion is facilitated (Table 2, TK1.2). Furthermore, the information exchange addresses cross-company management, so potential capacities of storage and logistics shall be identified in order to utilize free capacities optimally (Table 2, TK1.3). The procurement, recycling and disposal processes shall be managed efficiently by merging external services and (infra-) structure for joint usage and better purchasing and payment conditions, resulting in mutual cost reduction and higher revenues due to increased capacity utilization.

Another component is the facilitated synergy identification of IS opportunities, which covers match-making algorithms including output-input as well as supply-demand resources such as technologies, human resources, expertise, storage and logistics in order to enable the identification of potential cooperation partners in a defined geographical radius, for example, to identify same suppliers and disposal companies or to match input-output flows (Table 2, TK2.0). The integration of expert systems can round off a concept for an IT-supported IS tool and advance the functional spectrum of an IS web application (Table 2, TK2.3). A first preliminary concept for an expert system is divided into three functionality components:

1) **Knowledge acquisition component** (creating and improving the knowledge base): Therefore, several IS activity patterns based on real concrete case studies and IS measures need to be gathered and stored, so that the IS tool can access the information and provide concrete recommendations. This requires the setup of (relational) databases, which comprises data and information of inter alia IS activities/measures, structural IS classification, and sector and material specific information. So, a comprehensive knowledge of the material and energy flows, their type, quantity and composition are essential (Li 2018). With such a knowledge/data base, concrete recommendations for IS action and connections can be suggested for the existing area under consideration.
2) **Problem solving component** (to process the knowledge base provided and find appropriate solutions): Very different models can be used both to represent knowledge and to draw conclusions. The following two models should be taken into account in the concept for an IT-supported IS tool, since the most suitable one should be selected automatically depending on the application context:

    - In *case-based systems* there is a case database, which contains concrete problems in their context including a description of the solution (IS activity/measurement catalogue). The system tries to find a comparable case for a given case in its database and to transfer its solution to the current case (so in this application context of IS systems, real concrete case studies).
    - *Rule-based systems* or Business Rule Management Systems (BRMS) are based on rules of the type "If A, then B". The rules therefore tend to follow general laws from which conclusions are to be drawn for concrete situations. (Business) Rules must usually be defined beforehand by human experts and entered into the system manually. For example, "if there is a company with an output flow of coal fly ash, then this material can be further utilized as fertilizer". The rules can be derived from a knowledge base to be developed (IS resource catalogue of compatible material exchanges) that needs to cover sector-specific resource data allowing compatible cross-sectoral resource output-input match-makings.

    Typical task classes for expert systems that are to be used in particular in the application context of the IT-supported IS tools are:

    - *Planning:* Generation and evaluation of action sequences to achieve target states
    - *Design:* Description of structures that meet given requirements
    - *Prognosis:* Prediction and evaluation of achievable states of time-varying systems

3) **Explanation component** (making the results/solutions understandable to the user): The IT-supported IS tool shall provide various visualization formats to present the results and recommendations for action (e.g., interactive Sankey diagrams, social networks, tables, input-output balances, statistics, written text).

The innovative part of the web application is the module of simulation and modelling (Table 2, TK3.0) which shall use methods of system dynamics and artificial intelligence (AI) algorithms such as Artificial Neural Networks (ANN) and/or hybrid-approaches of ABM and Reinforcement

Learning (a machine learning technique, sub-field of AI) (Lütje et al. 2019b). So, the web application should be able to simulate and model various transformation pathways with two anchor points: from the actual state to the desired future scenario which is aligned to the defined goals of, for example, "zero waste", "zero emission" or "CO2-neutral" park, or the IP pursues to align its business performance to the science based targets (SBT) (SBTi 2019)[4]. Therefore, the underlying AI algorithms need to "learn" from several IS activity patterns and data based on real concrete case studies and stored IS measures. This requires the setup of a (relational) database, which contains all the required sector and material specific information. Of particular importance are the databases of IS material exchanges, IS activities/measures and structural IS formations for creating templates/blueprints and IS actions with their respective numeric data which the AI algorithms can use for the training and testing phase (learning process). With the help of iterative and combinatorial application of the individually deposited IS measures/templates, appropriate transformation pathways and concrete recommendations for IS actions can be simulated and modelled. Additionally, the phase of IS identification can be tremendously accelerated, once the (relational) databases are developed. In order to track the performance and progress towards set (sustainability) goals, a performance indicator system should be defined by the IS entities (Table 2, TK3.3).

It is recommended to establish an overarching organizational unit (Li et al. 2017) for IS administration and management (Table 2, TK4.0), that can additionally serve as an administrator of the IT-supported IS tool (Lütje et al. 2019a).

In order to align the approach in a targeted manner, quantifiable goals must be defined (Table 2, NK1.1), which is crucial for the arrangement of suitable IS measures, guiding the IS trajectory in the context of sustainable development. What is the purpose of the intended IS activities? Regarding sustainability development, it is certainly advantageous to envision a desired future scenario of, for example, a "zero waste park", "zero emission park", "CO2-neutral park" in a co-creational manner. If even enough information about concrete IS activities is stored in the tool or in a linked database, scenarios of optimally used IS systems can be simulated and modelled with the help of system dynamics and/or AI methods (Table 2, NK1.2).

## 3. Discussion and Concluding Impulses for Future Research

IS can occur spontaneously due to economic motivation, but just up to a certain point, then it needs to be further driven to exhaust its full potential (Mirata 2004). Each IS system is embedded in geographical, structural, economic, cognitive, cultural, political, temporal and spatial environments, which determine and guide the development of IS systems and their potentially optimal activities. The success of the IS evolution is highly dependent on the level of trust, motivation/interests, willingness, readiness and openness of the entities involved, so beside the most known primary economic motivation (Heeres et al. 2004; Jackson and Clift 1998; Senlier and Albayrak 2011; Sakr et al. 2011), the social, ethical, organizational and technological factors are the crucial driving forces to exploit the full range of IS.

This work focuses the technology-enabled environment for IS system analysis, transformation simulation and goal-setting in order to enable and facilitate IS in IPs. Therefore, a first prototype has been already conceptualized (Lütje et al. 2019a) and implemented (the manuscript of the prototype is currently under review), covering the first component of multi-methods system analysis, and the framework for a (key performance) indicator system has been developed (Lütje and Wohlgemuth, 2020), which is to be incorporated into the web tool.

The proposed concept for a holistic IT-supported IS tool goes beyond the previous approaches of system analysis and IS identification as well as information and collaboration platform. The innovative elements in this approach are, on the one hand, the extension of perspective to future visions/scenarios and goal setting for elaborating target-oriented transformation pathways and, on

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4 Science based targets (SBT) were established by the Science Based Targets initiative to drive corporate climate action that is aligned to meet the goals of the Paris agreement in 2015—to limit global warming to well below 2 °C above pre-industrial levels.

the other hand, the inclusion of supporting simulation and modelling techniques. As Lütje et al. (2019b) proposed, hybrid approaches of ABM and Reinforcement Learning enable the investigation of system dynamics of IS and therefore open up the exploration of various transformation pathways from the actual state of an IP to the desired goal state of an IS system. Detailed research is needed to conceptualize and implement such approaches. So, topics of system analysis and IS identification are well recorded in the scientific and non-scientific literature, but there are still profound research gaps in the fields of normative and transformative knowledge, which should be prioritized in future research activities. Especially the elaboration of quantifiable goals (which can be in line with the Sustainable Development Goals (SDGs) of the United Nations (UN) and/or Science Based Targets (SBT)), their respective (key performance) indicators and the development of a corresponding roadmap with concrete IS measures should be addressed intensively in this research field.

The concept for a web application to be developed, presented in this paper, is an innovative and promising approach to enable the evolution of IS systems and requires further research especially in the field of building up respective databases in order to exhaust the full potential of the presented IT-supported IS tool. The buildup of such an (international) IS database should be part of future research and forms a cornerstone for the inclusion of system dynamics and AI methods as well as supporting expert systems, which accelerate IS identification. Information and data on IS structure and morphology as well as material exchanges can be basic properties that an ANN can use to characterize and classify IS network types. The prerequisite for the use of expert systems and AI techniques is essentially the development of (relational) databases that can be compiled from previous (non-)scientific literature.

However, still further research is suggested for the development of IT-supported IS information and integrated analysis tools. The existing literature should be analyzed in-depth in order to extract valuable IS knowledge (addressing system, transformative and normative knowledge) and to crystallize out general IS patterns, activities and core elements for the development of an expert system. The identification of common (key) patterns of IS systems are required relating to detailed IS structures, characteristics, attributes and causations. Future research could address for example:

- the detection of IS key entities in order to ensure resilient IS systems,
- the investigation of recurring composition patterns in IS systems (repetitious cooperating IS industries) in order to facilitate the recommendation of potential IS partners,
- the mapping of common resource exchange flows in IS systems (which output flows can function as which input flows?) in order to create an IS resource catalog for the facilitated recommendation of concrete IS resource flow connections.

This, in turn, can be used as a knowledge base for the transformation simulation to derive application rules, insights and to develop optimally utilized IS scenarios.

We need to keep in mind, that planet earth and its embedded ecosystems are not static states, but dynamic ones, which are connected and interfere with each other, so each subsystem cannot be considered separately. It is like a dynamic system that continuously tends to oscillate to a new equilibrium. The socio-economic-technological sphere is embedded in the global ecosystem; hence it is constrained by it regarding ecosystem functioning and ecosystem services to humankind. So, there are environmental impacts while the resources move within the socio-economic-technological sphere. For every step of recycling or processing of secondary raw materials, additional energy and resources are required. There is no "perpetuum mobile". We know, that if we continue the pathway of business as usual, we would gradually deprive ourselves of our own livelihood. We need to pose the crucial question: "How to shape and create safe operating activities within the planetary boundaries?" Moreover, as every human activity generates environmental impacts, we need to consider the "safe operating range" of human activities as well as in terms of compensation and balance. We need to find a sustainable pathway gradually and successively. From an anthropocentric point of view, global society needs to steadily converge to a consensus of what is bearable and proportionate for present and future generations concerning inter-, intra- and transgenerational justice.

## 4. Materials and Methods

This study aims to present the results for the software/system development process phase of Requirements Engineering (RE), also called requirements analysis, to elaborate an initial basic framework for a holistic IT-supported IS tool covering system analysis, transformation simulation and goal-setting. The first steps of RE focus on identifying software requirements, then detailing and refining them. By the first conception of a holistic IT-supported IS tool fundamentally crucial and trend-setting requirements are formulated here. The IS tool has been designed based on an extensive cross-case analysis. An extensive literature review, employing bibliometric analysis and snowballing techniques, was conducted to select a total of 105 freely accessible papers, including 75 case studies (see full list in Appendix A), to synthesize and abstract knowledge of Industrial Symbiosis (IS) in order to converge to possible answers of the research questions, displayed in Figure 3. The design of the research scheme is oriented to the three types of knowledge, which have its origins in the fields of transdisciplinarity and sustainability sciences (Lang et al. 2012), showing the iterative and recursive processes of gaining insights for system, transformative and normative knowledge.

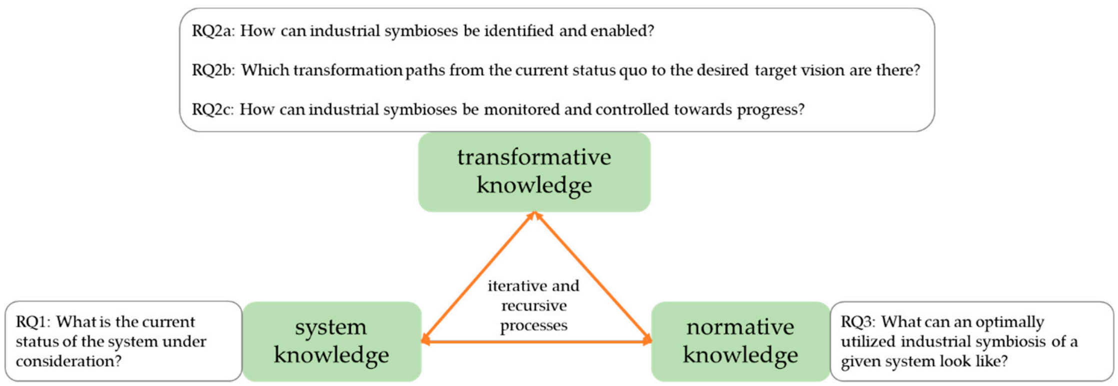


**Figure 3.** Research scheme and questions for the development of a systematic approach for IS Figure 75. Case studies were chosen with the non-probability sampling technique of purposive sampling. The initial sample size of 75 case studies was predetermined by the authors. The processes of qualitative data collection and analysis were conducted simultaneously. As a purposive sampling technique, the maximum variation sampling was applied in order to cover a wide range of perspectives and IS case studies, enabling the examination of software requirements and IS patterns across the sample case. When selecting the case studies, consideration was given to addressing a diverse set of different IS systems. Additionally, it was ensured to collect case studies from different periods, authors and geographical regions. Once a paper addressed the topics of: 1) (IT-supported) IS tool, 2) the application of a method in IS context, 3) representing IS case studies with mentioned concrete material exchanges and IS activities as well as 4) case studies addressing IS structures/morphologies, they were chosen for this paper. Only publications in English and German were included in the study due to reasons of language comprehension.

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## Appendix A

List of analyzed case studies.

| Nr. | Publication year | Main author | Publication Title | Region of IS system |
|---|---|---|---|---|
| 1 | 2014 | Alkaya et al. | Industrial Symbiosis in Iskenderun Bay: A journey from Pilot Applications to a National Program in Turkey. | Turkey |
| 2 | 2008 | Ashton | Understanding the organisation of Industrial Ecosystems - A social network approach. | Puerto Rico |
| 3 | 2010 | Bain et al. | Industrial Symbiosis and waste recovery in an Indian industrial area. | India |
| 4 | 2012 | Behera et al. | Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. | South Korea |
| 5 | 2008 | Chertow et al. | Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies. | Puerto Rico |
| 6 | 2009 | Chertow et al. | The social embeddedness of Industrial Symbiosis linkages in Puerto Rican industrial regions. | Puerto Rico |
| 7 | 2019 | Chertow et al. | Industrial symbiosis potential and urban infrastructure capacity in Mysuru, India. | India |
| 8 | 2014 | Chopra et al. | Understanding resilience in industrial symbiosis networks: Insights from network analysis. | Denmark |
| 9 | 2010 | Costa et al. | A case study of Industrial Symbiosis development using a middle-out approach. | Portugal |
| 10 | 2018 | Cui et al. | Understanding the Evolution of Industrial Symbiosis with a System Dynamics Model: A Case Study of Hai Hua Industrial Symbiosis, China. | China |
| 11 | 2010 | Dai | Two quantitative indices for the planning and evaluation of eco-industrial parks. | China |
| 12 | 2011 | Doménech et al. | Structure and morphology of industrial symbiosis networks: the case of Kalundborg. | Denmark |
| 13 | 2013 | Dong et al. | Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model. | China |
| 14 | 2016 | Dong et al. | Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China. | China |
| 15 | 2003 | Francis | The chemical industry from an industrial ecology perspective. | United States of America |
| 16 | 2014 | Geng et al. | Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone. | China |
| 17 | 2014 | Golev et al. | Industrial symbiosis in Gladstone: a decade of progress and future development. | Australia |
| 18 | 2011 | Hatefipur et al. | The Händelö area in Norrköping, Sweden - Does it fit for Industrial Symbiosis development? | Sweden |
| 19 | 2004 | Heeres et al. | Eco-industrial park initiatives in the USA and the Netherlands: first lessons. | United States of America and Netherlands |
| 20 | 2006 | Jacobsen | Industrial Symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. | Denmark |
| 21 | 2009 | Jyrki | Harjavalta industrial eco park—A success story of the industrial ecology in the area of metallurgical industry to increase regional sustainability. | Finland |

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| 22 | 2005 | Korhonen et al. | Analysing the evolution of industrial ecosystems: concepts and application. | Finland |
| 23 | 2013 | Laybourn | Opportunities through Industrial Symbiosis: UK NISP and Global Experience. | United Kingdom |
| 24 | 2011 | Li | A case study of Industrial Symbiosis: the Beijiang power plant complex in Tianjing, China. | China |
| 25 | 2015 | Li et al. | Industrial symbiosis as a countermeasure for resource dependent city: a case study of Guyang, China. | China |
| 26 | 2017 | Li et al. | The vulnerability of industrial symbiosis: a case study of Qijiang Industrial Park, China. | China |
| 27 | 2018 | Liu et al. | Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on emergy analysis. | China |
| 28 | 2009 | Liwarska-Bizukojc et al. | The conceptual model of an eco-industrial park based upon ecological relationships. | Austria |
| 29 | 2015 | Lu et al. | Ecological Network Analysis for Carbon Metabolism of Eco-industrial Parks: A Case Study of a Typical Eco-industrial Park in Beijing. | China |
| 30 | 2018 | Marconi et al. | An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment. | Italy |
| 31 | 2013 | Marinos-Kouris et al. | Environmental limits of industrial symbiosis: the case of aluminium eco-industrial network. | Greece |
| 32 | 2015 | Martin | Quantifying the environmental performance of an industrial symbiosis network of biofuel producers. | Sweden |
| 33 | 2011 | Martin et al. | Improving the environmental performance of biofuels with industrial symbiosis. | Sweden |
| 34 | 2018 | Martin et al. | Prospecting the sustainability implications of an emerging industrial symbiosis network. | Sweden |
| 35 | 2011 | Mathews et al. | Progress toward a circular economy in China. | China |
| 36 | 2017 | Mauthoor | Uncovering industrial symbiosis potentials in a small island developing state: The case study of Mauritius. | Mauritius |
| 37 | 2008 | Melanen et al. | Industrial Symbiosis for global climate change mitigation. | Finland |
| 38 | 2004 | Mirata | Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. | United Kingdom |
| 39 | 2005 | Mirata et al. | Industrial Symbiosis networks and the contribution to environmental innovation: the case of the Landskrona Industrial Symbiosis programme. | Sweden |
| 40 | 2019 | Morales et al. | "By-product synergy" changes in the industrial symbiosis dynamics at the Altamira-Tampico industrial corridor: 20 years of industrial ecology in Mexico. | Mexico |
| 41 | 2016 | Notarnicola et al. | Industrial Symbiosis in the Taranto industrial district: current level, constraints and potential new synergies. | Italy |
| 42 | 2010 | Pakarinen et al. | Sustainability and industrial symbiosis - The evolution of a Finnish forest industry complex. | Finland |
| 43 | 2010 | Park | Eco-industrial development in South Korea and its future | South Korea |
| 44 | 2008 | Park et al. | Strategies for sustainable development of industrial park in Ulsan, South Korea—From spontaneous evolution to systematic expansion of industrial symbiosis. | South Korea |
| 45 | 2008 | Pearce | Industrial symbiosis of very large-scale photovoltaic manufacturing. | United States of America |
| 46 | 2017 | Raabe et al. | Collaboration platform for enabling industrial symbiosis: Application of the by-product exchange network model. | Model |

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| 47 | 2004 | Roberts | The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study. | Australia |
| 48 | 2017 | Sacchi et al. | The effect of price regulation on the performances of industrial symbiosis: a case study on district heating. | Denmark |
| 49 | 2006 | Saikku | Eco-industrial parks: a background report for the eco-industrial park project at Rantasalmi. | Finland |
| 50 | 2011 | Sakr et al. | Critical success and limiting factors for eco-industrial parks: global trends and Egyptian context. | Egypt |
| 51 | 2007 | Sendra et al. | Material flow analysis adapted to an industrial area. | Spain |
| 52 | 2011 | Senlier et al. | Opportunities for sustainable industrial development in turkey: Eco-industrial parks. | Turkey |
| 53 | 2010 | Shi et al. | Developing country experience with eco-industrial parks: a case study of the Tianjin Economic Technological Development Area in China. | China |
| 54 | 2014 | Short et al. | From Refining Sugar to Growing Tomatoes: Industrial Ecology and Business Model Evolution. | United Kingdom |
| 55 | 2014 | Simboli et al. | Analysing the development of Industrial Symbiosis in a motorcycle local industrial network: the role of contextual factors. | Italy |
| 56 | 2010 | Sokka et al. | Analyzing the Environmental Benefits of Industrial Symbiosis - Life Cycle Assessment Applied to a Finnish Forest Industry Complex. | Finland |
| 57 | 2018 | Song et al. | Social network analysis on industrial symbiosis: A case of Gujiao eco-industrial park. | China |
| 58 | 2016 | Sun et al. | Eco-benefits assessment on urban industrial symbiosis based on material flow analysis and emergy evaluation approach: a case of Liuzhou City, China. | China |
| 59 | 2017 | Taddeo et al. | The development of Industrial Symbiosis in Existing Contexts. Experiences from three Italian clusters. | Italy |
| 60 | 2012 | Ulhasanah et al. | Preliminary Design of Eco-City by Using Industrial Symbiosis and Waste Co-Processing Based on MFA, LCA, and MFCA of Cement Industry in Indonesia. | Indonesia |
| 61 | 2016 | UNIDO | Eco-industrial parks in emerging and developing countries: Achievements, good practices and lessons learned, a comparative assessment of 33 cases in 12 emerging and developing countries. | various countries |
| 62 | 2007 | Van Beers et al. | Industrial Symbiosis in the Australian minerals industry: the cases of Kwinana and Gladstone. | Australia |
| 63 | 2009 | Van Berkel et al. | Quantitative assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. | Japan |
| 64 | 2016 | Velenturf | Promoting industrial symbiosis: empirical observations of low-carbon innovations in the Humber region, UK. | United Kingdom |
| 65 | 2015 | Wen et al. | Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China´s Suzhou New District. | China |
| 66 | 2008 | Yang et al. | A case study of industrial symbiosis: Nanning Sugar Co., Ltd. in China. | China |
| 67 | 2019 | Yazan et al. | Sustainable operations of industrial symbiosis: an enterprise input-output model integrated by agent-based simulation. | Numeric example model |
| 68 | 2018 | Yazdanpan-ah et al. | Industrial Symbiotic Networks as Coordinated Games. | Model |
| 69 | 2015 | Yu et al. | Evolution of industrial symbiosis in an eco-industrial park in China. | China |
| 70 | 2009 | Yuan et al. | Improving enterprise competitive advantage with industrial symbiosis: case study of a smeltery in China. | China |

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| 71 | 2015 | Zabaniotou et al. | Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill. | Italy |
| 72 | 2013a | Zhang et al. | Social network analysis and network connectedness analysis for industrial symbiotic systems: model development and case study. | China |
| 73 | 2013b | Zhang et al. | Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: A case study with carbon flow analysis. | China |
| 74 | 2015 | Zhang et al. | Ecological network analysis of an industrial symbiosis system: A case study of the Shandong Lubei eco-industrial park. | China |
| 75 | 2018 | Zhu et al. | Industrial Symbiosis in China. A Case Study of the Guitang Group. | China |

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## 6. Paper 3: Tracking Sustainability Targets with Quantitative Indicator Systems for Performance Measurement of Industrial Symbiosis in Industrial Parks

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*Article*

# Tracking Sustainability Targets with Quantitative Indicator Systems for Performance Measurement of Industrial Symbiosis in Industrial Parks

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**Abstract:** Industrial Symbiosis (IS) is a systematic and collective (business) approach to optimizing the use of materials and energy among cross-sectoral industries in order to initiate and exhaust extended cascading systems; it is associated with (synergistic) environmental, technical, social, and economic benefits. For monitoring and controlling the development and progress of an IS system, an indicator system must be set up to standardize and assess the IS (sustainability) performance. This study aims to present a quantitative indicator system to enable the tracking of set sustainability targets of an IS system in Industrial Parks (IPs) for goal-directed IS management. The presented guiding framework encourages IP members in IS systems to set sustainability objectives and to evaluate and track their performance over time with a quantitative indicator system. In particular, established and (partly) internationally standardized methods—such as Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA), Social Network Analysis (SNA), and Life Cycle Assessment (LCA)—are used in order to place the indicator system on a solid and robust foundation and to adequately meet the multi-faceted sustainability perspectives in the form of a combinatorial application for deriving suitable quantitative indicators for all three (environmental, economic, social) dimensions of sustainability. The indicator system, once embedded in an Information Technology (IT)-supported IS tool, contributes crucially to the technology-enabled environment of IS systems, driving sustainability trajectories.

**Keywords:** industrial symbiosis; industrial ecology; indicator system; sustainability targets; resource efficiency; resource productivity; sustainability performance measurement

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## 1. Introduction

Industrial Symbiosis (IS) is a systematic and collective (business) approach to optimizing the use of materials and energy among cross-sectoral industries (Chertow 2004; Herczeg et al. 2016) in order to initiate and exhaust extended cascading systems; it is associated with (synergistic) environmental, technical, social, and economic benefits (Ehrenfeld and Gertler 1997; Chertow 2004; van Berkel et al. 2009; Sokka et al. 2010; Herczeg et al. 2016; Chertow et al. 2019; Domenech et al. 2019). "Industrial symbiosis, as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. ( . . . ) Industrial symbiosis engages traditionally separated industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and synergistic possibilities offered by geographic proximity." (Chertow 2000, pp. 313–14). Li (2018) defines IS as the exploration of "ways to establish knowledge webs of novel material, energy, and waste exchanges and business core processes to facilitate the development of networks of synergies within and across different companies to support the development of high levels of nearly closed-loop material exchanges and efficiency of energy cascading within and across industrial ecosystems." (Li 2018, p. 35). This implies cross-sectoral collaboration within industrial communities by connecting the supply and demand of various companies (van Berkel et al. 2009; van Capelleveen et al. 2018; Domenech et al. 2019) through the exchange of material, energy, water, and human resources (Herczeg et al. 2016; Ruiz-Puente and Bayona 2017; Chertow et al. 2019).

This can be achieved through controlled resource and information flows at the inter-company level, facilitated by cross-organizational Information Technology (IT)-supported IS tools. The progress and development of IS software tools offer various opportunities for many applications in IS systems, especially for the identification of IS activities and synergistic connections, resource and information flow management, relationship management of the IS actors, and community building, amongst others. For monitoring and controlling the development and progress of an IS system, an indicator system must be set up to standardize and assess the IS (sustainability) performance. As Liu et al. (2018) stated, there is no agreed indicator system for an IS system. Therefore, this study aims to present a quantitative indicator system to enable the tracking of set sustainability targets of an IS system in Industrial Parks (IPs) for goal-directed IS management. The presented guiding framework encourages IP members in IS systems to set sustainability objectives and to evaluate and track their performance over time with a quantitative indicator system. The indicator system, once embedded in an IT-supported IS tool, contributes crucially to the technology-enabled environment of IS systems, driving sustainability trajectories.

## 2. Results

### *2.1. Industrial Symbiosis Case Studies*

Figure 1 shows the schematic overview of a company's production process with the corresponding input and output resource flows, which already indicate the points of contact for IS activities, leading to economic, environmental, and social benefits. It was derived from the analyzed IS case studies to extract and abstract the points of contact for IS possibilities.

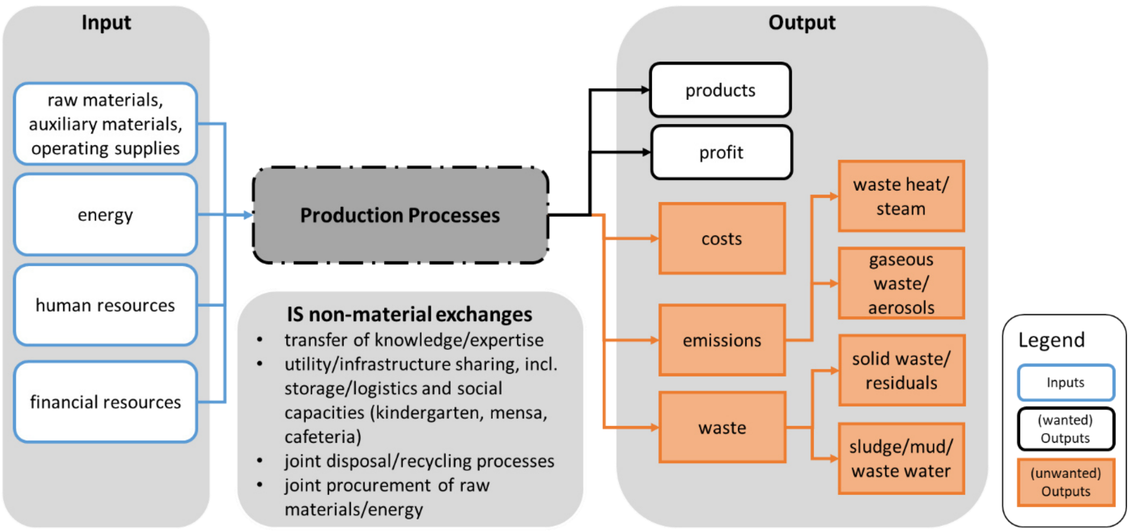


**Figure 1.** Schematic overview of a company's points of contact for Industrial Symbiosis (IS) activities.

In this IS context, many companies re-evaluate their "waste" streams as new business opportunities or extended business models. For example, waste heat/excessive steam can be forwarded to other companies (Mirata 2004; Pakarinen et al. 2010; Yu et al. 2015; Earley 2015).

A smeltery in China recovered raw materials out of gaseous waste/aerosol, sludge/mud, and solid waste by filtering, extracting, concentrating, and compressing the resources out of each waste stream (Yuan and Shi 2009). The Guitang Group in China approached a disposal problem by using their sludge as the calcium carbonate feedstock for a new cement plant while reducing residual and waste flows (Zhu et al. 2008).

Gaseous/aerosol waste streams such as fly ash can be further processed as cement additives (Dong et al. 2013; Golev et al. 2014; Cui et al. 2018) or soil additives (Notarnicola et al. 2016; Bain et al. 2010).

Wastewater from food processing companies (such as olives, cereals, fruit, and vegetables) can be further utilized as fertilizer (Chertow 2008; Notarnicola et al. 2016) or for the irrigation of agricultural land; the respective organic residual (solid) waste can be re-processed to animal/fish feeding (material utilization) (Chertow 2007; Alkaya et al. 2014) or biogas and biofuel (energetic utilization) (Alkaya et al. 2014). The digestate of a biogas plant can further serve as fertilizer (Martin 2013; Alkaya et al. 2014).

Furthermore, IS activities can lead to the buildup of IS networks not only across different supply chains, but also along the supply chain of one industry. For example, Yang and Feng (2008) investigated the Chinese IS of the Nanning Sugar Industry, which incorporated affiliated companies centered around their core business of sugar production to (re-)process the residual and waste flows of the mother company (Yang and Feng 2008). Enterprises of cane farming, paper, alcohol, health products, and the cement industry were all located at the upstream or the downstream of the main sugar production, extending their own core business to an entire IS supply chain (Yang and Feng 2008). These IS activities led to various environmental, social, and economic benefits; for example, reduced costs, pollution controlling fees and environmental impacts, new jobs, and innovation for advanced business models were created, and the supply of raw materials and material quality were ensured (Yang and Feng 2008). Additionally, a sugar company in the Ulsan Industrial Park in South Korea had similar experiences by expanding the company's own collection of downstream companies, generating new revenues (Park et al. 2008). With the utilization of almost all residual and waste flows of sugar production, a better product quality was achieved, as well as reduced environmental emissions and disposal costs (Park et al. 2008).

### *2.2. Applied Methods in Industrial Symbiosis Systems*

IS systems can be investigated by various quantitative methods (Kastner et al. 2015). Table 1 presents an overview of the methods applied in the context of IS systems. Certainly, there are other methods that can be used in the IS context (Kastner et al. 2015); the ones listed here refer exclusively to the results of the conducted case study analysis, which revealed three core methods that have been applied most: Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Social Network Analysis (SNA). These findings are very close to congruent to the results of other researchers (Kastner et al. 2015; Felicio et al. 2016; Li et al. 2017; Huang et al. 2019), who ascertained that the most widely used methods for IS systems are MFA (Geng et al. 2012; Sendra et al. 2007; Yong et al. 2009), LCA (Sokka et al. 2010; Sokka et al. 2011), and environmental indicators (Kurup and Stehlik 2009; Pakarinen et al. 2010; Zhu et al. 2010).

According to the three dimensions (ecological, economic, social) of sustainability, the results of the case study analysis revealed that most of the applied methods cover the environmental aspects (SFA, MFA, emergy analysis, exergy analysis, eLCA); only one method addresses both the economic (MFCA) and social aspects (SNA). Furthermore, it shows that the environmental LCA (eLCA) was predominantly applied in the context of IS systems.

**Table 1.** Overview of methods applied in the context of IS systems.

| Method | Description | References |
|---|---|---|
| Social Network Analysis (SNA) | Investigates social structures of networks and characterizes elements within the network in terms of nodes (e.g., individual actors, companies, people) and the connecting ties or links (relationships or interactions). | (Ashton 2008; Doménech and Davies 2009; Doménech and Davies 2011; Zhang et al. 2013; Chopra and Khanna 2014; Song et al. 2018) |
| Substance Flow Analysis (SFA) | Quantifies and traces the flows and stocks of one specific substance/chemical or a group of substances within the system under consideration. | (Zhang et al. 2013; Wen and Meng 2015) |
| Material Flow Analysis (MFA) | Quantifies the flows and stocks of materials and energy of the system under consideration in physical units (e.g., kg), distinguishing between input and output streams of the respective processes. | (Chertow 2008; Park et al. 2008; Yang and Feng 2008; Zhu et al. 2008; van Berkel et al. 2009; Yuan and Shi 2009; Bain et al. 2010; Ulhasanah and Goto 2012; Sun et al. 2016; Li et al. 2017; Taddeo et al. 2017; Mauthoor 2017; Morales et al. 2019) |
| Material Flow Cost Accounting (MFCA) | Traces and quantifies the flows and stocks of materials and energy of the system under consideration in physical and monetary units; especially the material losses, non-/by-product, and waste flows are evaluated. | (Viere et al. 2011; Ulhasanah and Goto 2012; Lütje et al. 2018; Lütje et al. 2019a) |
| Life Cycle Assessment (LCA) | Quantifies the flows and stocks of materials and energy of the system under consideration and assesses the associated environmental impacts, such as global warming and eutrophication potential. | (Sokka et al. 2010; Ulhasanah and Goto 2012; Marinos-Kouris and Mourtsiadis 2013; Sacchi and Ramsheva 2017; Marconi et al. 2018; Martin and Harris 2018; Chertow et al. 2019) |
| Emergy analysis | Emergy is an expression of all the energy consumed in direct and indirect transformations in the processes to generate a product or service; therefore, emergy analysis converts the thermodynamic basis of all forms of energy, resources, and human services into equivalents of a single form of energy (usually solar emjoules). | (Geng et al. 2014; Sun et al. 2016; Liu et al. 2018) |
| Exergy Analysis | Is a thermodynamic analysis technique, assessing the thermodynamic performance of processes and systems, identifying the causes and locations of thermodynamic losses. | (Seager and Theis 2002) |

### 2.3. *Quantitative Indicator System*

Figure 2 shows the guiding framework for the sustainability performance of an IS system; its content and approach design is oriented to the three types of knowledge (system, transformative, and normative knowledge), which have their roots in the fields of transdisciplinarity and sustainability sciences (Lang et al. 2012). From this (normative) sustainability perspective, the IS entities could envision a desired future state of their IS systems; this could be, for example, a "zero waste", "zero emission," or "CO2-neutral" park, or that the IP pursues to align its business performance to the science-based targets (SBT)[1] (SBTi 2019). After investigating the status quo of the system under consideration, possible future scenarios could be developed with the method of scenario planning (beginning from the actual state). In accordance with the defined goals or pursued sustainability trajectory, scenarios of optimally utilized IS systems can be developed. Once the desired future vision is defined, various transformation pathways from the desired future to the actual state can be elaborated

[1] Science-based targets (SBT) were established by the Science-Based Targets initiative to drive corporate climate action that is aligned to meet the goals of the Paris agreement in 2015—to limit global warming to well below 2 °C above pre-industrial levels.

with the method of backcasting (planning possible measures/milestones backward, which then will be operated forward). This process can include all share- and stakeholders.

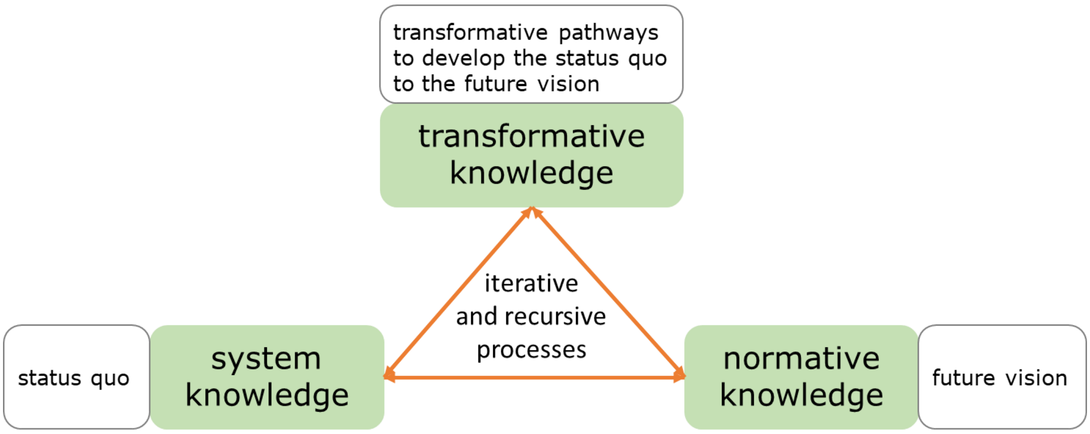


**Figure 2.** Guiding framework for the sustainability performance of an IS system.

By setting up a sustainability (key performance) indicator system which is in line with the quantifiable goals, the progress of the IS system can be continuously tracked and monitored. If an overarching organizational unit or a core team of the IS system is established, it could control and push the IS performance towards the trajectory of circular economy and sustainable development. Defining the (sustainability) goal of the IS system is crucial in order to arrange the approach and transformative pathways (corresponding suitable IS measures) in a targeted manner.

A general guiding systematic approach can support the development process of an indicator system:

1. **What is the overall purpose of the IS system?**

An example of an answer could be: To contribute to sustainable development and circular economy.

2. **According to which (gradual) goals and criteria should the IS system be aligned?**

This could be, for example, a target orientation towards a "zero waste", "zero emission", "CO2-neutral", or SBT park.

3. **What are requirements of the IS system?**

One possible answer could be: The essential requirements of an IS system can be summarized briefly: (1) Optimize/maximize the social and economic benefit, (2) minimize environmental burden, and (3) operate as a resilient and adaptive system. Thus, the overall sustainability contribution of an IS system can be assessed as an increase in resource productivity and efficiency, with positive social impacts and a continuously well-operating system.

4. **What should be measured?**

As already displayed in Figure 1, inputs of financial, human, and environmental (material, water, energy, land use) resources are required, and simultaneously, outputs of economic, social, and environmental impacts are generated. Each category of input- and output-related resources and impacts can be measured by specific indicators.

## 5. How should these be measured?

In such a systematic framework, input-related indicators—addressing financial, human, and environmental resource properties—and output-related indicators—addressing economic, social, and environmental impact categories—can be developed.

Once the IP sets its quantitative indicator system, a base year shall be chosen and measured so that a time series can be tracked for each indicator. Then, a balance sheet can be implemented, in which the absolute and relative change values in relation to the values of the base year of each individual indicator can be recorded. This approach enables goal-directed IS management, while the continuous improvement processes and the yearly progresses of the IS system can be traced by the indicator time series (referenced to a base year). If necessary, measures can be taken if the performance does not correspond to the desired progress. It is recommended to define an overarching target for the entire IP and a respective roadmap with quantifiable targets and milestones to ensure a goal-oriented IS management.

On the basis of the systematics developed, the indicators were derived and further developed in line for the IS performance measurement. The following general, environmental, economic, and social indicator sets do not claim to be exhaustive, but should be successively extended and derived from common methods and standards to facilitate a systematic approach and data collection/analysis. They represent example systems that can be adapted according to the specific target orientation of each IS system, which is defined by the IP itself, since the objectives and priorities are set by the respective members of the industrial estate.

An IS general indicator system was developed for the aspects of IS structure, IS activity, IS knowledge transfer, IS system resilience, and adaptability (Table 3). It can be set up in order to generate an overview of the current state and activity level of the IS system and to get a glimpse of where the journey can go in terms of IS (sustainability) performance. The special indicators are resilience and system adaptability. Valenzuela-Venegas Guillermo et al. (2018) developed a resilience indicator which is based on two sub-indicators: The network connectivity index and flow adaptability index. The network connectivity index considers the number of connections among the entities while evaluating the minimum and maximum number of connections, in order to measure the endurance of the entire network system against possible disruptive events (e.g., loss of an entity) (Valenzuela-Venegas Guillermo et al. 2018). The flow adaptability index quantifies the necessary (material) flows and the capacities of the entities to compensate a disruption in the system (e.g., fluctuating material flows) (Valenzuela-Venegas Guillermo et al. 2018).

**Table 2.** IS general indicator system.

| Indicator | Unit | References |
|---|---|---|
| **IS Structure** | | |
| number of overarching/special IS organizational units | # | (UNIDO 2019; own suggestions) |
| number of participating entities in the IS system | # | |
| density of IS system | $\frac{\#\ IS\ entities}{\#\ entities\ in\ entire\ IP}$ | |
| number of joint disposal companies | # | |
| number of joint supplier companies | # | |
| number of joint logistics companies | # | |
| **IS Activity** | | |
| number of IS connections | # | (UNIDO 2019; own suggestions) |
| degree of interconnectivity | $\frac{\#\ IS\ connections}{\#\ IS\ entities}$ | |
| number of exchanged resources | # | |
| degree of resource exchange activity | $\frac{\#\ exchanged\ resources}{\#\ IS\ entities}$ | |
| number of water networks | # | |
| activity degree of water network | $\frac{m^3 IS\ water\ network}{m^3\ IP\ water\ consumption}$ | |
| number of material networks | # | |
| activity degree of material network | $\frac{kg\ IS\ material\ network}{kg\ IP\ material\ consumption}$ | |
| number of energy networks | # | |

**Table 3.** IS general indicator system.

| Indicator | Unit | References |
|---|---|---|
| **IS Activity** | | |
| activity degree of energy network | $\frac{MWh\ IS\ energy\ network}{MWh\ IP\ energy\ consumption}$ | |
| number of knowledge networks | # | |
| number of IS meetings addressing IS measures | # | |
| number of identified IS opportunities | # | |
| number of planned IS activities | # | |
| number of IS activities that are being implemented | # | |
| number of implemented IS activities | # | |
| number of IS consultations | # | |
| number of IS system analyses | # | |
| investments in IS consultations | $ | |
| investments in IS system analyses | $ | |
| investments in IS measures | $ | |
| received (public) funding to expand IS system | $ | |
| **IS Knowledge Transfer** | | |
| number of education/training events addressing IS | # | (UNIDO 2019; own suggestions) |
| number of educated/trained persons concerning IS | # | |
| **IS System Resilience and Adaptability** | | |
| network connectivity indexflows adaptability index | | (Valenzuela-Venegas Guillermo et al. 2018) |

Table 4 shows an IS environmental indicator system, specialized to the performance of IS cascading loops/systems (resources, emissions, etc. saved through IS activities). It differentiates input- and output-related indicators. While most of the presented indicators are easier to understand, the following two require further explanation:

**Table 4.** IS environmental indicator system.

| Indicator | Unit | References |
|---|---|---|
| **Input-Related Indicators** | | |
| saved primary material resources | kg | (Krajnc and Glavič 2003; Trokanas et al. 2014; Valenzuela-Venegas Guillermo et al. 2018; Chertow 2008; Park et al. 2008; Yang and Feng 2008; Zhu et al. 2008; van Berkel et al. 2009; Yuan and Shi 2009; Bain et al. 2010; Ulhasanah and Goto 2012; Sun et al. 2016; Li et al. 2017; Taddeo et al. 2017; Mauthoor 2017; Morales et al. 2019; Sokka et al. 2010; Marinos-Kouris and Mourtsiadis 2013; Geng et al. 2014; Sacchi and Ramsheva 2017; Marconi et al. 2018; Martin and Harris 2018; Chertow et al. 2019; UNIDO 2019) |
| saved primary water resources | $m^3$ | |
| saved primary energy resources | MWh | |
| saved land use | $m^2$ | |
| recycled solid waste | kg | |
| recycled liquid waste/water | $m^3$ | |
| recycled/used gaseous/aerosol waste | $m^3$ | |
| material recovery rate | % | |
| recycled water rate | % | |
| renewable energy produced in the IS system | MWh | |
| **Output-Related Indicators** | | |
| reduced CO2 emissions | kg CO2e | (Sokka et al. 2010; Ulhasanah and Goto 2012; Marinos-Kouris and Mourtsiadis 2013; Geng et al. 2014; Sacchi and Ramsheva 2017; Marconi et al. 2018; Martin and Harris 2018; Chertow et al. 2019; UNIDO 2019) |
| reduced NOx emissions | kg NOx | |
| reduced SO2 emissions | kg SO2 | |
| change in chemical exergy | J/mol | (Seager and Theis 2002; Valenzuela-Venegas Guillermo et al. 2018) |
| Relative Emergy Savings (RES) | solar emjoules | (Geng et al. 2014; Sun et al. 2016; Valenzuela-Venegas Guillermo et al. 2018; Liu et al. 2018) |

Generally, energy consists of two parts: Exergy and anergy. Exergy is the part of the total energy of a system that is actually usable and can do work, anergy is the total opposite. The general relationship between exergy and the material life cycle involves high-exergy resources (low entropy) being extracted from the environment, processed and consumed by the economy, and returned to the environment as low-exergy materials, i.e., waste (high entropy) (Seager and Theis 2002). So, over the phases of the entire life cycle, exergy is reduced, while the share of anergy and entropy increases; i.e., in order to keep a system at a certain level, new usable energy must be supplied and consumed "from outside" again and again.

Emergy is an expression of all of the past work performed by the environment, economy, and society in the entire process chain to generate a product or service (incl. all of the energy consumed in direct and indirect transformations). Due to the incorporation of all previous work and services, an emergy sustainability index is a single comprehensive, aggregated indicator, and can represent the sustainability performance of the system under consideration (Sun et al. 2016). By studying the Shenyang Economic and Technological Development Zone (SETDZ) in China, Geng et al. (2014) found out that emergy indicators are not all-encompassing measures of environmental and economic performances, but are appropriate to indicate the overall performance of one IP, especially when these are complemented with other methods and respective indicators. For example, the emergy indicator of relative emergy savings (RES) can be defined as the ratio of avoided inputs through all of the IS activities to total emergy inputs without related IS activities (Geng et al. 2014). Furthermore, this indicator can be extended to consider the entire life cycles of products and services.

Table 5 shows an IS economic indicator system. The input- and output-related indicators generally address cost savings achieved through IS activities. While most of the presented indicators are simple to understand, the following two require further explanation:

**Table 5.** IS economic indicator system.

| Indicator | Unit | References |
|---|---|---|
| **Input-Related Indicators** | | |
| cost savings for human resources | \$ | (Ulhasanah and Goto 2012; Lütje et al. 2018; Lütje et al. 2019a; UNIDO 2019) |
| cost savings for material | \$ | |
| cost savings for water | \$ | |
| cost savings for energy | \$ | |
| cost savings for land use | \$ | |
| production-cost-specific IS cost savings | $\frac{IS\ cost\ savings\ (\$)}{production\ costs\ (\$)}$ | |
| Emdollar value of Total Emergy Savings (ETS) | \$ | (Geng et al. 2014; Sun et al. 2016; Liu et al. 2018) |
| **Output-Related Indicators** | | |
| cost savings for disposal/recycling | \$ | (Trokanas et al. 2014; own suggestions) |
| cost savings for CO2 taxes | \$ | |
| cost savings for (CO2) emission trading certificates | \$ | |
| created added value | \$ | |
| created yield | \$ | |
| specific resource productivity | $\frac{yield\ (\$)}{unit\ resource}$ | (Wen and Meng 2015) |
| yield-specific IS cost savings | $\frac{IS\ cost\ savings\ (\$)}{yield\ (\$)}$ | own suggestions |
| specific area-related IS value-added ratio | $\frac{IS\ value-added\ (\$)}{area\ used\ (m^2)}$ | |

A resource productivity indicator (RP) can reflect the interlinked relation between economic growth and specific material consumption, indicating the circular economy performance of an IS system (Wen and Meng 2015).

The Emdollar value of total emergy savings (ETS) represents the economic benefits gained by IS activities (Geng et al. 2014).

Table 6 shows an IS social indicator system. These indicators mainly address non-material IS exchanges, whereof the employees of the IP can benefit socially by establishing joint utility and infrastructure projects of kindergarten, mensa, canteen, cafeteria, or cross-company organized mobility.

**Table 6.** IS social indicator system.

| Indicator | Unit | References |
| --- | --- | --- |
| **Input-Related Indicators** | | |
| created number of jobs | # | (UNIDO 2019; Geng et al. 2012) |
| number of joint organized social/charity events within the IS system | # | own suggestions |
| investments in joint/cross-company organized social activities | $ | |
| number of utility-sharing and joint infrastructure projects | # | |
| investments in utility-sharing and joint infrastructure (kindergarten, mensa, canteen, cafeteria, mobility) | | |
| **Output-Related indicators** | | |
| through shared IS utilities and human resources: improved environmental, health, and safety (EHS) aspects (e.g., number of trainings, audits, workshops, activities) | # | (Azapagic and Perdan 2000; UNIDO 2019; own suggestions) |
| improved working conditions (e.g., number of joint bargaining activities, number of joint organizations for kindergarten, canteen, cafeteria, mobility) | # | |

## 3. Discussion and Future Research

One of the crucial first steps of this approach is the necessity of defining sustainability objectives to which the IP members in the IS system commit, as well as the system analysis of the status quo, in order to develop a roadmap with respective measures. By setting up a sustainability indicator system which is in line with the quantifiable goals, the progress of the IS system can be continuously tracked and monitored. If an overarching organizational unit or a core team of the IS system is established, it could control and push the IS performance towards the trajectory of circular economy and sustainable development. Once the corresponding sustainability contribution of IS can be evaluated in a quantifiable manner, it can thus significantly influence the further course of IS implementation and can promote the full exhaustion of IS potentials.

This work presented a holistic indicator system covering all three dimensions of sustainability. While various methods and indicators have been developed for the economic and environmental dimensions, the highest development potential and challenge lie in the setup of a social indicator system, as the social dimension is tricky to quantify. In order to build a holistic indicator system, all of the strengths and weaknesses of chosen methods and indicators must be taken into account; an indicator is just a small puzzle piece of an image of reality, which is embedded in the context of a holistic system, and is thus a number to be interpreted with caution and in relation to the overall setting.

Nevertheless, in addition to advanced technology solutions, a systematic structuring in the form of quantitative indicator systems for measuring the sustainability performance of IS systems can make a further contribution to the technology-enabled environment of IS systems. After defining the sustainability goals of the IS system, appropriate measures can be prioritized and implemented, which in turn can be tracked and monitored with an indicator system. The challenge is to formulate a common sustainability goal for the IS system and to develop informative indicators accordingly. The meaningfulness and information content of individual indicators should also be assessed carefully; for a holistic view, a large number of different indicators from the three sustainability dimensions should always be included in order to avoid a view that is too one-sided. In addition, the relations of cost–benefit and cost–value must be proportionately added; processes like data collection and evaluation also consume financial and human resources. That is why this developed indicator system is to be embedded in an IT-supported IS tool, which facilitates continuous system analysis and tracking of the IP´s performance with quantitative indicators in a manageable manner for the participating companies (Lütje et al. 2019a).

Through the ongoing corporate digitalization (including data collection and processes), companies can track their economic, social, and ecological performance through advanced and smart Information and Communication Technology (ICT). IPs may evolve into Smart Industrial Parks (SIP) with intelligence monitoring, information processing, and risk prevention (Li et al. 2017). Sophisticated Environmental Management Information Systems (EMIS) need to be established within IPs to provide a reliable data and analysis basis for more valuable information and substantiated decision making which considers all three sustainability pillars and their respective (potential) trade-offs among them. It is therefore all the more important to establish a (standardized) indicator system in order to track progress towards sustainable trajectories and/or the defined objectives of the IS entities. Such an indicator system needs to be compatible with the goals defined by the IS entities, which can be, for example, a zero-waste, zero-emission, CO2-neutral park. This will be embedded in an overarching IT-supported IS tool (which has been already prototyped), enabling the presentation of updated or real-time indicators from entered data of the participating entities and the provision of the current status of the IS system. Future research will address a virtual simulation of an IS system, pursuing a sustainability target (e.g., converging to a zero-waste park), which will be tracked by a compatible set of indicators applying an IT-supported IS tool. From a visionary perspective, a standardized quantitative indicator system could allow benchmarking possibilities in the future and IS performance comparisons on a regional or (multi-)national scale, up to an international scale.

In the context of IS systems, the application of concepts such as Industry 4.0, Artificial Intelligence (AI) (Lütje et al. 2019b), Smart Industrial Parks (SIP), etc. can provide promising solution approaches in order to remarkably advance the research area and scope of action of IS, and hence significantly drive the dynamics and speed of (further) development of IS systems.

## 4. Materials and Methods

This study is embedded in an overarching work project, addressing the development of an IT-supported Industrial Symbiosis (IS) tool for the identification of IS opportunities and management of IS in Industrial Parks (IPs). The development of an IS web tool was designed based on previous research activities (Figure 3). Requirements Engineering (RE), also called requirements analysis, is one of the main activities of the software or system development process, which defines the requirements for the system to be developed with the help of a systematic procedure from the project idea of the goals to a complete set of requirements. This was underpinned by extensive systematic literature research and analysis of existing case studies, as well as interviews with IS experts and practitioners. Based on that, a first prototype was developed, deploying methods such as Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA), Social Network Analysis (SNA), and Life Cycle Assessment (LCA, optionally) in a combinatorial approach for the IS context. These methods were identified to be the most applied and well-established approaches in IS systems (Lütje et al. 2019a; Huang et al. 2019; Li et al. 2017; Kastner et al. 2015).

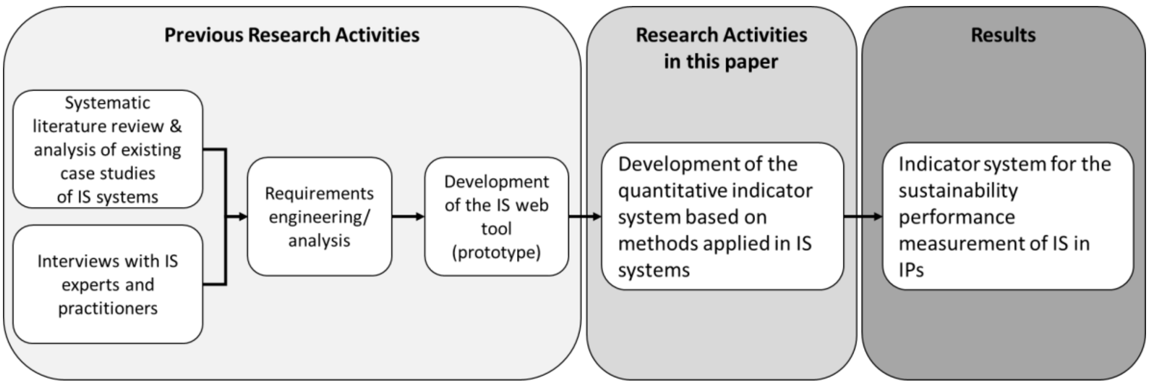


**Figure 3.** Design of the research approach.

A comprehensive systematic literature review, deploying forward and backward snowballing techniques, was carried out to analyze a total of 70 freely accessible papers, including 55 case studies, to extract knowledge of IS for the following research question (RQ): *How can the sustainability performance of an IS system (especially industrial parks) be measured and tracked?*

Publications were sourced from the following databases, such as Thomson Reuters Web of Knowledge, ResearchGate, google scholar, Scopus, CORE, and Directory of Open Access Journals. The queries searched for the following terms: "Industrial symbiosis", "industrial symbiosis indicator", and "(smart/eco) industrial park". The selection of scientific papers was aligned to three aspects, so once a paper addressed the topics of: 1) The application of a method in an IS context, 2) IS case studies, 3) (social, environmental, economic) indicators in an IS context, they were chosen for this study. Only publications in English and German were included in the study.

This paper deals with the development of an indicator system to measure and track the IS sustainability performance in IPs towards set sustainability targets over time. This is then integrated into the IS web tool in order to be able to automatically present updated or real-time indicators from the entered data. The presented indicators were derived from the implemented methods and analyzed literature. The indicators were aligned to the following system matrix, which covers the three dimensions (environmental, social, economic) of sustainability (Table 7).

**Table 7.** Design of the indicator matrix.

| | **Environmental Dimension** | **Economic Dimension** | **Social Dimension** |
|---|---|---|---|
| **Input-Related Indicators** | e.g., through IS saved primary resources | e.g., through IS saved primary material costs | e.g., through IS created jobs |
| **Output-Related Indicators** | e.g., through IS reduced emissions | e.g., through IS saved disposal costs | e.g., through IS improved working conditions |

It differentiates process/production input- and output-related indicators, while referring to either environmental, social, or economic resources and impacts. Furthermore, a general indicator system was deduced, differentiating indicators for the following aspects: IS structure, IS activity, IS knowledge transfer, IS system resilience, and adaptability.

On the one hand, this structuring of the system matrix shall ensure a systematic indicator set balancing all three dimensions of sustainability in order to meet the multi-faceted perspectives of sustainable development. On the other hand, differentiated input- and output-related indicators highlight "localized" points of contact, as well as leverage or intervention points, to guide appropriate measures for improving the sustainability performance of IS systems. Quantifiable sustainability goals and their respective indicators, once incorporated into an IT-supported IS tool, enable the systematic tracking of set sustainability targets in the technology-enabled environment of IS systems, guiding sustainability trajectories.

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## 7. Paper 4: Recurring Patterns and Blueprints of Industrial Symbioses as Structural Units for an IT Tool

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# Recurring Patterns and Blueprints of Industrial Symbioses as Structural Units for an IT Tool

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**Abstract:** Industrial Symbiosis (IS) deals with the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple material and energetic (re-)utilization within industrial systems. To facilitate the technology-enabling environment of IS systems, this work deals with the identification of recurring patterns in IS systems of specific IS case studies and deduction of elementary blueprints and structural units, setting an initial cornerstone to pool and synthesize existing IS knowledge and to deploy this knowledge base in an Information Technology (IT)-supported IS tool, which would remarkably advance the scope of action and development of IS systems. An explorative cross-case analysis was conducted by investigating 80 IS case studies in depth in order to illuminate recurring (key) patterns in IS systems by generalizing and abstracting IS main structures, compositions, resource exchange activities and measures. It has been shown that similar IS sectoral partnerships and resource exchanges have recurrently formed in different regions and hence, generalizable patterns can be deduced. This study identified common IS compositions, sector clusters and key/core/anchor entities and synthesized a content basis for a database of an IS resource exchange catalog based on existing/available IS information, which can be used in an IT-supported IS tool. It contains information of specific IS resource exchanges, broken down by industrial sectors, differentiating providing and receiving sectors and which respective exchanged waste flows were processed into which secondary material/product. Once this fundamental information/data base is incorporated and applied in an IT-supported IS tool, it enables the facilitated recommendation of potential IS partners and IS actions to optimize existing IS cases or to initiate IS development. Especially, first IS germ cells of (key) entities can be derived and connected to each other considering individual circumstances and (geographical) business environments.

**Keywords:** industrial symbiosis; industrial ecology; patterns; IT-supported tool; resource productivity; resource efficiency

## 1. Introduction

Today's era is called "the Anthropocene" [1], as human activities have become the main driver of global change. Global challenges such as climate change, increasing freshwater consumption, chemical pollution [2] and limited resource availability have emerged and triggered social, governmental and economic activities. In order to stay within the planetary boundaries [2], ecosystem functioning and services to human societies need to be maintained in a safe operating range. These complex and partly interdependent challenges need to be approached in an appropriate and comprehensively sophisticated way to meet the multi-faceted perspectives of sustainable development. This encompasses, among other things, fields of action for reduction of wastes, emissions, primary resource and energy consumption. So circularity and resource efficiency measures are emerging priorities on the European Union (EU) policy agenda [3].

One of the application concepts in industrial contexts is Industrial Symbiosis (IS), which deals with the set-up of advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple material and energetic (re-)utilization within industrial systems. IS is a collaborative cross-sectoral approach to connect compatible resource input and output flows of production systems across different companies in order to optimize the resource use through exchanges of material, energy, water (and non-material exchanges such as human resources and joint management processes), while generating ecological, technical, social and economic beneficial synergies [4–6].

Beside the economic motivation of companies (e.g., cost savings), especially environmental regulations are considered to be pushing forces for companies to increase/improve their environmental performances and to become involved in IS systems [7,8]. But several hindering factors for companies to develop IS measures have been recognized, among others, there is a general lack of awareness of IS concepts [7–9], a lack of knowledge of IS possibilities, a lack of information sharing among locators [7,9], a lack of an institutional support for integration, coordination and communication, a lack of technology and infrastructure readiness [7] and difficulties in reaching agreements [8] and reaching fair cost/benefit allocation among the entities.

When it comes to practical implementation/initiation processes of IS, inter-organizational communication and information exchange is crucial [9,10]. [11] examined 17 IS tools in their study, whereat most of them are either inoperative or not publicly available today. Most of the investigated IS tools focus on output-input matchings of various resource flows among industrial actors, functionality and technical opportunities, but do not provide comprehensive decision support [11]. [12] studied 20 European IS supporting information technology tools and pointed out, that the newer IT tools developed in Europe considered the improvement potentials identified by [11]. Nevertheless, [12] stated, that "matchmaking tools and assessment methodologies hold the most promise for innovation for academia, IT tool developers and the facilitators of industrial symbiosis". All investigated tools focus on the as-is analysis of the IS system and the identification of IS measures. However, possible future scenarios as well as conceivable transformation paths from the actual state to the desired target vision (e.g., zero waste park) are not addressed at all and represent a substantial research and knowledge gap.

To date, many research studies were conducted to investigate various IS systems and to gain knowledge about IS opportunities and (initiation and operating) mechanisms, but as [13] pointed out, there are difficulties to extract and process useful information from the extensive available sources of data and knowledge. Especially companies still struggle to retrieve easy-to-understand information [14] and to integrate current IS knowledge into business processes [15]. All the mentioned observations have driven the current work, which aims to facilitate the technology-enabling environment for IS initiation, management and continuous improvement as a mean to exhaustively exploit IS potentials for leveraging sustainable industrial development and to provide easy-to-use business support to industrial actors and to increase user friendliness and IS adoption in industrial systems, because the barriers of inter alia lack of knowledge of IS possibilities, a lack of information sharing among companies are significantly lowered. This study is embedded in an overarching project, addressing the development of a holistic Information Technology (IT)-supported IS tool covering an information exchange platform among industrial actors, system analysis (identification of IS potentials via quantitative methods such as Material Flow Analysis), transformation simulation (e.g., dynamic supply-demand match makings within an IS system) and sustainability goal-setting [16]. As inter-company information exchange is crucial to identify and implement IS opportunities [9,10,17–19], the proposed IT-supported IS tool shall provide companies with easy-to-understand, structured and specific information as well as specific recommendations for actions regarding potential IS activities to business users. Within this project an IS expert system, which is to be integrated into the IT-supported IS tool [16] and a hybrid-approach of agent-based modelling (ABM) and Reinforcement learning (Machine Learning technique) for simulating the dynamics of IS systems [20] are being developed. An expert system is a computer program that derives recommendations for action from a knowledge/data base like a human expert [21]. ABM deals with computer-aided modelling and simulation of (inter-/re-)actions of autonomous agents (which represent individuals or collective entities/groups) in order to assess their effects on the entire system [22].

So this foundation work is needed, on the one hand, to apply existing knowledge/data base to the expert system which enables the recommendation of IS activities, facilitating input-output/supply-demand matchings and further IS potentials in the specific area under consideration, and on the other hand, to derive suitable rule definitions for the virtual agents of the hybrid-ABM to interact properly and to converge to possible scenarios of goal-defined states of IS systems (e.g., "zero-waste IS parks"). To facilitate the technology-enabling environment of IS systems, this work deals with the identification of recurring patterns in IS systems of specific IS case studies and deduction of elementary blueprints and structural units of IS systems, setting an initial cornerstone to pool and synthesize existing IS knowledge and to deploy this knowledge base in an IT-supported IS tool, which would remarkably advance the scope of action and development of IS systems.

## 2. Methods

This research focus to approach answers of the research question (RQ): Which recurring patterns can be identified in existing Industrial Symbiosis systems and which elementary blueprints and structural units can be deduced for the deployment in an IT-supported tool? Therefore, an explorative cross-case analysis was conducted by investigating 80 IS case studies in depth (see full list in Table 1) in order to illuminate recurring (key) patterns in IS systems by generalizing and abstracting IS main structures, compositions, resource exchange activities and measures.

For each case study, the following information is extracted in the form of an exploration and evaluation matrix:

1. IS main structures and compositions:
   - Participating sector-specific entities: were documented for the investigation of recurring composition patterns in IS systems in order to identify repetitious cooperating IS industries (specific IS sector clusters) for the facilitated recommendation of potential IS partners and blueprint-IS network constellations.
   - IS key/core/anchor entities: were detected based on the identified IS sector clusters.
   - IS structures: and characteristics, attributes and causations were abstracted in order to break down elementary IS archetype formations, which can be used to build structural IS systems.
2. IS activities and measures:
   - Material, energy, (waste) water, knowledge and utility exchanges: The different exchange types and their relative occurrence are identified. Material exchanges were defined as material, solid waste, by-product and residual flows which were exchanged between at least two entities. Energy exchanges were defined as all energy flows between at least two entities covering thermal, steam, (process/waste) water for heating or cooling reasons, power/electricity, (bio-)gas, (bio-)fuel flows. (Waste) water exchanges were defined as all (process/waste) water flows which were used as secondary raw material or process water in another entity. Knowledge exchanges were defined as all coordinated information, data and knowledge/expertise sharing between at least two entities through for example an organizational (network) unit, third party consultancy or an (IT-supported) information system. Utility sharing was defined as shared infrastructure and services which are operated/organized jointly, e.g., joint management of procurement and disposal/recycling processes, kindergarten, cafeteria.

Common IS resource exchanges: mapping of compatible output-input flows in order to synthesize an IS resource exchange catalog for the facilitated recommendation of blueprint IS resource flow connections and measures in an IT-supported IS tool.

Case studies were selected with the non-probability sampling technique of purposive sampling.

Purposive sampling, also known as selective sampling, was chosen to be able to draw theoretical, analytic and logical generalizations from the sample of IS case studies [23]. As a purposive sampling technique, the maximum variation sampling, also known as heterogeneous sampling, was applied in order to cover a diverse set of IS case studies and clusters as well as a wide range of IS system attributes concerning structure/composition and resource exchange activities, enabling the investigation and identification of common and recurring IS patterns across the sample case [23]. Therefore, it was ensured to collect case studies from different authors, publication periods and geographical regions, whereas each location-based case study was explicitly considered once. Case studies were chosen once they provided detailed descriptions of the investigated IS system concerning composition of the involved entities, exchanged resources and their respective connectivities (including papers presenting feasible/potential/suggested, planned and implemented IS measures, whereat most of the analyzed case studies are operational IS systems). The initial sample size of 80 case studies was predetermined by the authors. Among them are 46 case studies provided by the IS database Total Resource and Energy Efficiency Management System for Process Industries (MAESTRI), a library of IS case studies and linked exchanges, which contains 424 reported IS exchanges [24]. The entire dataset sums up to 617 IS resource exchanges. The processes of qualitative data collection and analysis were conducted simultaneously.

Publications were sourced from the following databases such as ResearchGate, google scholar, Scopus, Thomson Reuters Web of Knowledge, CORE, Semantic Scholar and Directory of Open Access Journals. The queries searched the following terms "industrial symbiosis" and "(smart/eco) industrial park". Only publications in English and German were included in the study due to reasons of language comprehension.

The gathered qualitative and categorical data were analyzed and visualized with RStudio (RStudio is an open source tool for data science and statistical analysis and visualization (https://rstudio.com/)), using the following R packages: library(networkD3), library(igraph), library(reshape2), library(readxl), library(ggplot2), library(ggpubr), library(tm), library(tau), library(plyr), library(dplyr), library(readr), library(plotly). The balloon plot of Figure 1 (visualizing multivariate categorical data), the network plots (Publicly available online: https://www.codementor.io/@jhwatts2010/counting-words-with-r-ds35hzgmj) of Figures 2 and 4 and the radar plot (Publicly available online: https://www.codementor.io/@jhwatts2010/counting-words-with-r-ds35hzgmj) of Figure 3 were implemented with publicly available R codes which were adapted to the dataset. The IS network clusters were developed by mapping respective Nomenclature of Economic Activities (NACE) (Full list of NACE codes: http://www.export.gov.il/files/EEN/ListNACEcodes.pdf) codes to a source and target edge-list (a two-column matrix defined by start and end vertices).

**Table 1.** List of analyzed case studies (alphabetically sorted by regions and IS/Eco-Industrial Park (EIP) names).

| Nr. | References | IS/EIP Name | Region of IS System |
|---|---|---|---|
| 1 | [25] | Heavy Industrial District Gladstone | Australia |
| 2 | [26] | Kwinana Industrial Park | Australia |
| 3 | [27] | Ecopark Hartberg | Austria |
| 4 | [28] | Waste disposal network Styria | Austria |
| 5 | [29] | Industrial Symbiosis Cluster Koekhoven | Belgium |
| 6 | [30] | Norte Fluminense industrial area | Brazil |
| 7 | [31] | Steelmaking, Cement Manufacturing, Zinc Smelting Cluster | Brazil |
| 8 | [32] | Burnside Industrial Park | Canada |
| 9 | [33] | Beijiang Power Plant Complex | China |

| | | | |
|---|---|---|---|
| 10 | [34] | Circuit board industry in Suzhou New District | China |
| 11 | [35] | Guitang Group | China |
| 12 | [19] | Gujiao Eco-Industrial Park | China |
| 13 | [36] | Hai Hua Industrial Symbiosis | China |
| 14 | [37] | Harbin Yingbin Eco-Industrial Park | China |
| 15 | [38] | Hazardous waste symbiosis network | China |
| 16 | [39] | Iron and steel industrial Park in Gansu | China |
| 17 | [40] | Jinan City | China |
| 18 | [41] | Liuzhou City | China |
| 19 | [42] | Lubei National Eco-industrial Demonstration Park | China |
| 20 | [43] | Midong | China |
| 21 | [44] | Nanning Sugar Co. Ltd. | China |
| 22 | [45] | Qijiang Industrial Park | China |
| 23 | [46] | Rizhao Economic and Technology Development Area | China |
| 24 | [47] | Shenyang Economic and Technological Development Zone | China |
| 25 | [48] | Smeltery | China |
| 26 | [42] | Suzhou Industrial Park | China |
| 27 | [49] | Tianjin Economic & Technical Development Area (TEDA) | China |
| 28 | [50] | Yongcheng | China |
| 29 | [51] | Sustainable Industrial Network Program (SINP) | Colombia |
| 30 | [52] | Industrial Area of Aalborg | Denmark |
| 31 | [53] | Kalundborg | Denmark |
| 32 | [54] | Monfort Boys Town Integrated Biosystem | Fiji |
| 33 | [5] | Kymi Mill in Kouvola | Finland |
| 34 | [55] | Pulp and paper mill on the river Kymijoki in Kuusankoski | Finland |
| 35 | [56] | Rantasalmi Eco-industrial Park | Finland |
| 36 | [57] | Uimaharju | Finland |
| 37 | [58] | Harjavalta industrial eco park | Finland |
| 38 | [59] | Dunkirk | France |
| 39 | [60] | Industrial Symbiosis in an Industrial zone | France |
| 40 | [28] | Recycling Network Ruhr Area | Germany |
| 41 | [28] | Waste disposal network Emden-Dollart Port | Germany |
| 42 | [61] | Nea Karvali | Greece |
| 43 | [6] | Mysuru | India |
| 44 | [62] | Business cluster in Mysore in the State of Karnataka | India |
| 45 | [63] | Cement Industry | Indonesia |
| 46 | [64] | Halmahera Eco-Industrial Estate | Indonesia |
| 47 | [65] | Abruzzo Region - Bussi Chemical Site (BCS) | Italy |
| 48 | [66] | Agro-Food context of IS in L`Aquila | Italy |
| 49 | [66] | Automotive context of IS in Chieti | Italy |
| 50 | [67] | Tanneries in S. Croce sull´Arno | Italy |
| 51 | [68] | Taranto industrial district | Italy |
| 52 | [69] | Waste Electrical and Electronic Equipment (WEEE) cluster | Italy |
| 53 | [70] | Eco-Town Kawasaki | Japan |
| 54 | [71] | Tanegashima | Japan |
| 55 | [72] | Three major polluting industries | Mauritius |
| 56 | [59] | Altamira-Tampico industrial corridor | Mexico |
| 57 | [73] | Eco-Industrial Park in Mongstad | Norway |
| 58 | [74] | Hayatabad Industrial Estate | Pakistan |
| 59 | [75] | Reguengos de Monsaraz Industrial Symbiosis Network | Portugal |
| 60 | [76] | Relvão Eco Industrial Park | Portugal |
| 61 | [77] | Barceloneta | Puerto Rico |
| 62 | [77] | Guayama Industrial Symbiosis | Puerto Rico |
| 63 | [78] | Ten IS systems | several |
| 64 | [79] | Food Waste Industrial Symbiosis Network | Singapore |
| 65 | [80] | Ulsan Eco-Industrial Park | South Korea |
| 66 | [81] | Forssjö | Sweden |
| 67 | [82] | Händelö | Sweden |
| 68 | [56] | Jämtland | Sweden |
| 69 | [83] | Landskrona Industrial Symbiosis | Sweden |
| 70 | [81] | Mönsterås | Sweden |
| 71 | [84] | Norrköping | Sweden |
| 72 | [85] | Sotenäs IS network | Sweden |

| | | | |
|---|---|---|---|
| 73 | [81] | Värö | Sweden |
| 74 | [86] | Ecosite Geneva | Switzerland |
| 75 | [87] | Iskenderun Bay | Turkey |
| 76 | [88] | Humber Region Industrial Symbiosis Programme (HISP) | United Kingdom |
| 77 | [88] | West Midlands Industrial Symbiosis Programme (WISP) | United Kingdom |
| 78 | [89] | By-Product Synergy Central Gulf Coast Project | USA |
| 79 | [90] | Food Cycling in New Haven | USA |
| 80 | [91] | General Motors | USA |

## 3. Results

### *3.1. Patterns in Industrial Symbiosis Structures and Compositions*

#### 3.1.1. Industrial Symbiosis Compositions, Clusters and Key Entities

The cross-case analysis revealed recurring (key) patterns in existing IS systems concerning IS structures, compositions/clusters and resource exchanges. The multivariate frequency distribution in Figure 1 shows the occurrence of corresponding IS sectors in the investigated 80 case studies. In all 80 case studies were processing and manufacturing entities present, in 76 cases recycling and recovering entities, in 53 energy producing entities, in 39 wastewater treatment entities, in 39 waste treatment entities, in 34 agricultural entities, in 15 urban/local entities, in 10 forestry entities, in 9 aquacultural entities and in 9 cases mining entities were involved. The first quarter top left shows the main industry clusters that participate together in IS systems. It points out the fundamental functioning of an IS system, which mimics the essential mechanisms of ecological resource metabolisms, covering producers (e.g., primary resource extraction/production, agriculture, energy industries), primary/secondary/n consumers (e.g., processing and manufacturing industries) and destruents/remineralizers (e.g., water and resource recycling).

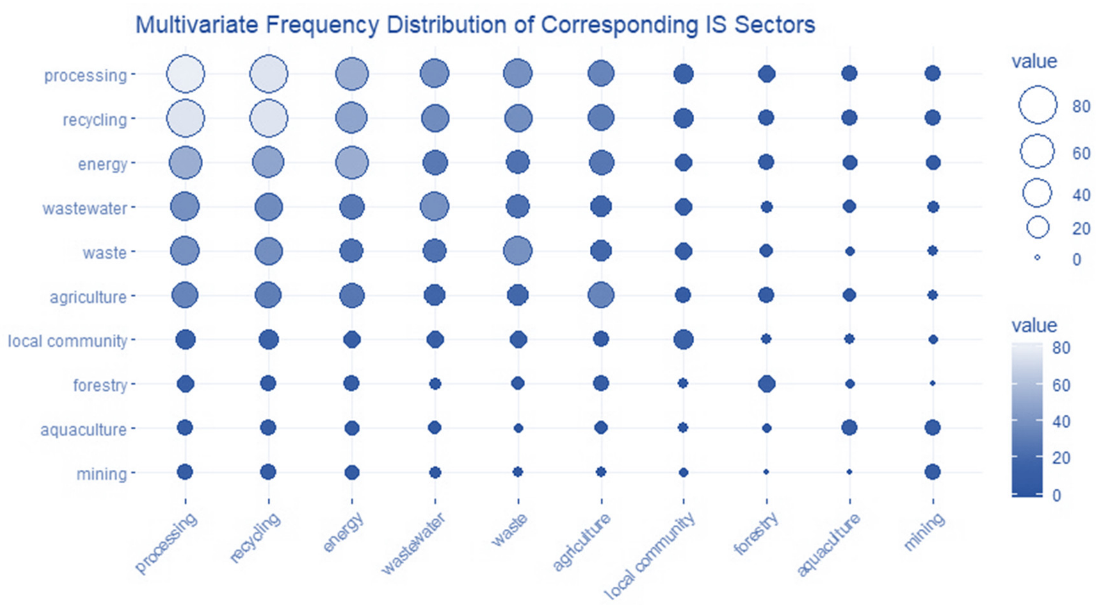



**Figure 1.** Balloon plot showing the multivariate frequency distribution of corresponding IS sectors.

Each entity in an IS system can act as an originator/provider and/or receiver of IS resource exchanges. Having analyzed 617 IS resource exchanges with their respective providing and receiving sectors, the following network diagram resulted (Figure 2). It appears to be very interconnected and to have a core center of multiple anchor entities/sectors with multilateral connections to associated entities/sectors in the periphery. Based on the underlying dataset, this indicates that there are several (key) clusters and sectors in IS systems, which strongly function as key connections between different

IS cluster networks. Together with Figure 3, it is shored up that predominantly the key sectors comprise:

1. NACE code 0110: Growing of non-perennial crops,
2. NACE code 1020: Processing and preserving of fish, crustaceans and mollusks,
3. NACE code 1081: Manufacture of sugar,
4. NACE code 1101: Distilling, rectifying and blending of spirits,
5. NACE code 1710: Manufacture of pulp, paper and paperboard,
6. NACE code 1920: Manufacture of refined petroleum products,
7. NACE code 2015: Manufacture of fertilizers and nitrogen compounds,
8. NACE code 2059: Manufacture of other chemical products,
9. NACE code 2351: Manufacture of cement,
10. NACE code 2410: Manufacture of basic iron and steel and of ferro-alloys,
11. NACE code 3511: Production of electricity,
12. NACE code 3521: Manufacture of gas,
13. NACE code 3821: Treatment and disposal of non-hazardous waste,
14. NACE code 4120: Construction of residential and non-residential buildings,
15. NACE code 4211: Construction of roads and motorways,
16. NACE code NA: urban entities.

This results are close to congruent to the findings of [14].

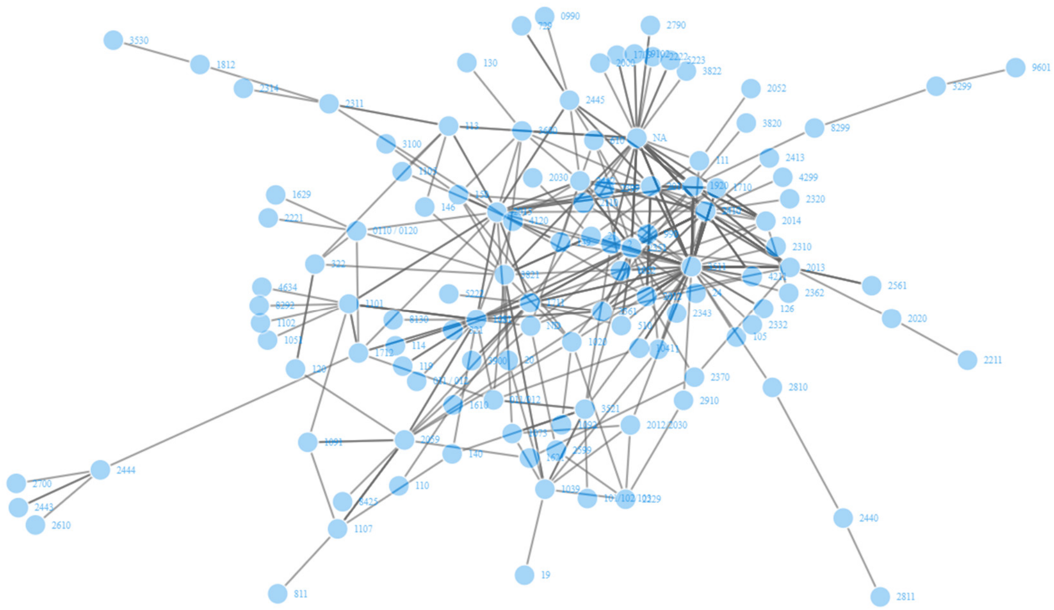



**Figure 2.** Network diagram of cooperating IS sector clusters.

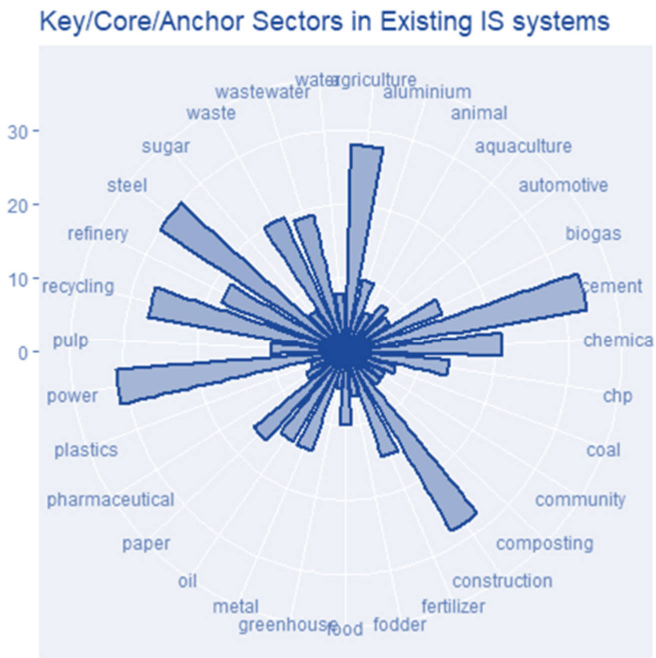



**Figure 3.** Radar plot of occurrence of key/core/anchor sectors in IS systems (sectors with > = 5% occurrence were included).

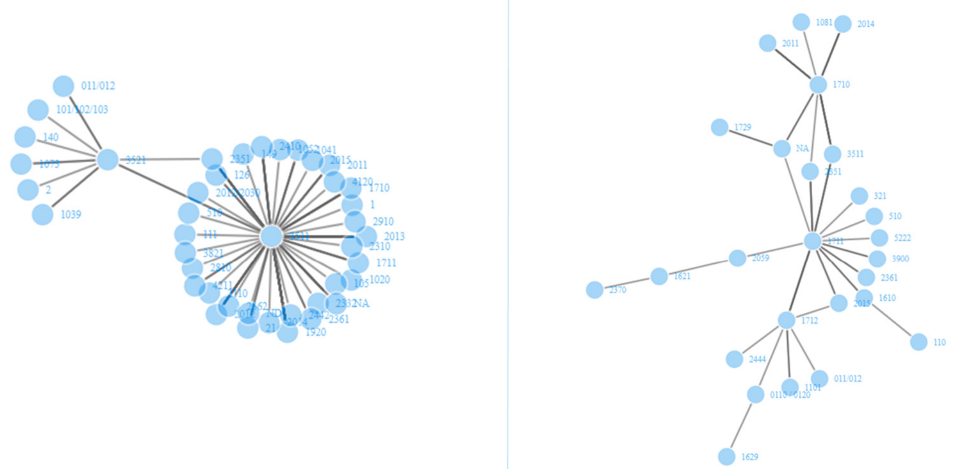
As the network diagram in Figure 2 is very complex and hard to comprehend, detailed network diagrams of six exemplary key IS sector clusters were created to depict their in-depth relationships. Figure 4a) presents the network around NACE code 35 (electricity, gas, steam and air conditioning supply) with its subfield 3511 production of electricity, it is outstanding due to its centrality in the entire IS cluster structure and is connected as a providing sector to a distributed set of receiving sectors, mainly in the manufacturing field. For example, [82] explored the Händelö IS in Sweden, which contains an ethanol, biogas and combined heat and power (CHP) plant, producing renewable biofuels, district heating and electricity, supplying various industries and the local community.

Figure 4b displays the network cluster around NACE code 17 (manufacture of paper and paper products) with its subfield 1710 manufacture of pulp, paper and paperboard, which is mainly linked to the fields of cement (2351), concrete (2361), energy (3511), chemical production (2059/2015) and urban entities (NA). Materials of (waste) wood and (waste) paper are much-demanded in different sectors not only for material but first of all for energetic re-utilization. For example, [5] investigated a Finnish IS network, centered around a pulp and paper mill, which includes a chlorine dioxide, a calcium carbonate, a hydrogen peroxide, a water purification, a wastewater treatment and a power plant, fired with wood residues and pulp and paper sludge. The power plant provides heat and electricity for the pulp and paper mill and the local town [5]. The three chemical plants supply the pulp and paper mill with chemicals and the chlorine dioxide and the calcium carbonate plants obtain energy and purified water from the pulp and paper mill [5]. The calcium carbonate plant reuse the carbon dioxide emissions from the flue gases of the pulp and paper mill as a raw material [5].

Figure 4c,d illustrate the intertwined and close relationships of the cement (23) and metal (24) industries, in which especially blast furnace (BF) and steel slags are donated to be processed as cement, concrete, bricks and tiles additives. Also industries of basic metals, chemicals/fertilizers, energy, coke and refined petroleum products conglomerate to an IS cluster. For example, [70] studied the Kawasaki Eco-town in Japan, which is an IS system of metal, concrete, cement, ammonia and paper production. The steel company reprocessed plastic wastes to feed it as reducing agents and fuels to the BF for steel production, whereas the concrete company reused plastic wastes as secondary raw materials for the manufacturing of concrete formwork [70]. The (paper) sewage sludge, BF and steel slag, surplus soil from construction sites, soot dust/(coal) fly ash and burnt residues/incineration ash from the local incinerators are inserted as alternative raw materials for cement production, while plastic wastes and waste tires are predominantly used as fuel alternatives to coal [70].

Figure 4e,f show the strong relationship between the chemical/fertilizing sector and agriculture, which is a big receiving sector for many waste types that can be reprocessed into fertilizers or soil additives. Sugar production (1081) is directly linked to agricultural production (011/012), especially through sugarcane farming, from that a variety of other sectors are connected, e.g., alcohol production (1101). For example, the Guitang Group in China established an IS system consisting of entities of sugarcane farming, sugar mill/refinery, cement, alkali recovery, calcium carbonate, alcohol, pulp and paper and fertilizer production [35]. The sugarcane from the farming fields are transferred to the sugar mill and refinery, where the waste outputs of molasses are further processed in the alcohol plant and the alcohol residues are forwarded to the production of compound fertilizer, which is directed back to the sugarcane fields [35]. The other waste outputs (carbonation filter mud and bagasse) of the sugar mill and refinery are processed in the cement production, whereas bagasse is passed on to the pulp and paper mill (as 60% of the bagasse has fibers long enough for paper-making) and the short fibers of the pith are used as fuel in a CHP plant [35]. The carbon dioxide emissions of the sugar refinery are used as input material for the calcium carbonate plant, which again is connected to the cement mill. The alkali recovery plant recycles the waste from the pulping operation (black liquor), generating a white sludge which is additionally used in the cement mill [35].

Across the investigated case studies, it crystallizes out that repetitious relationships among various (key) sectors exist and are well reflected in the network diagrams.



a) sector source NACE code 35 (electricity, gas, steam and air conditioning supply, especially 3511 production of electricity)

b) sector source NACE code 17 (manufacture of paper and paper product, especially 1710 pulp and paper)

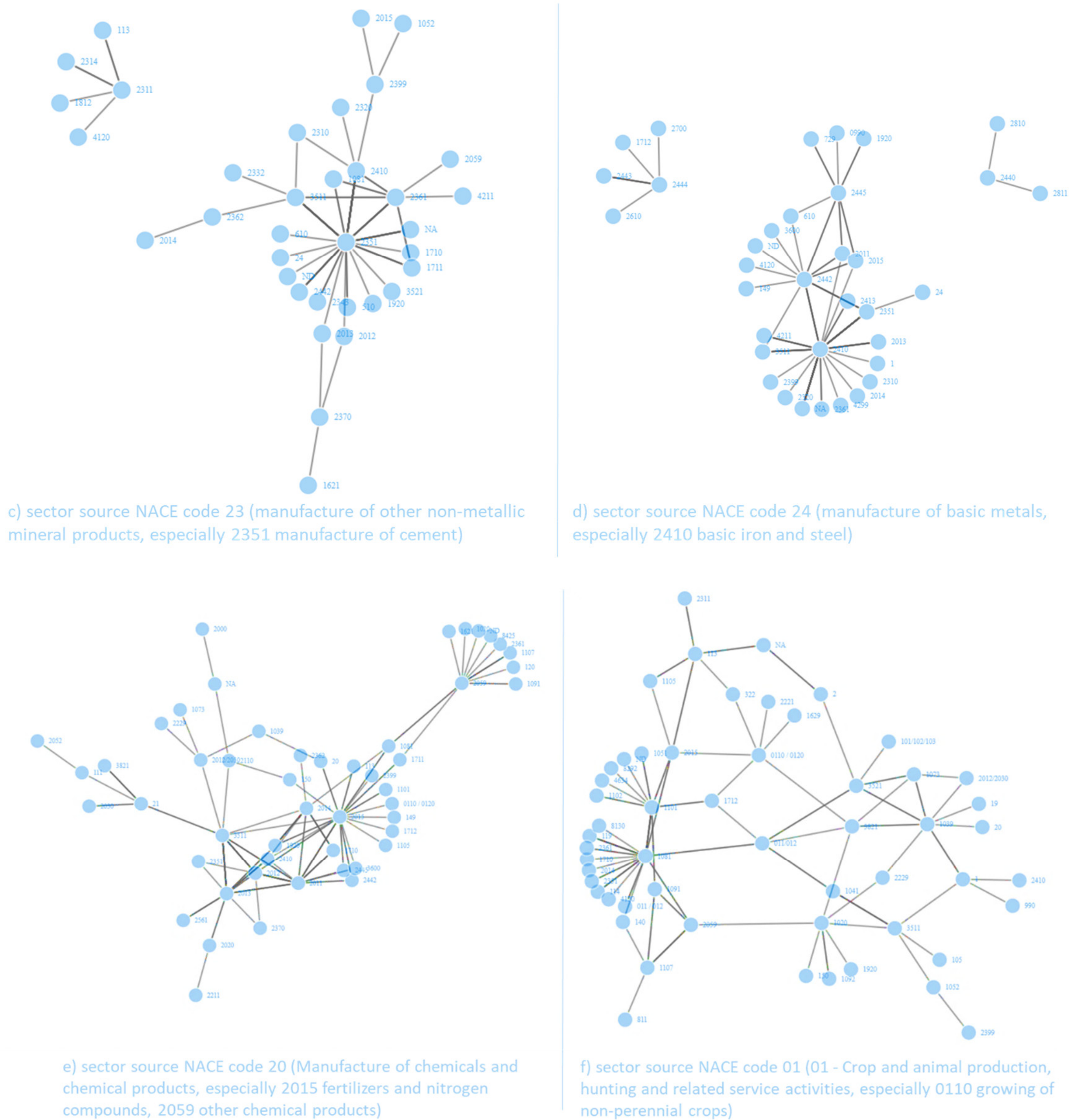



**Figure 4.** Six exemplary network diagrams of IS clusters with specific sector source NACE codes.

### 3.1.2. Classification of Structural Industrial Symbiosis Archetype Formations

Based on the 80 analyzed case studies, the following classification of structural IS archetype formations was deduced. The structural formation depends on the (geographical) business environments and possible IS resource exchange connections, the number of connections (connected entities) and the tie direction, shaping various archetype structures as displayed in Figure 5. Each classified structure was generalized and simplified to demonstrate the various elementary IS formations, which an IS system can be built on. The following case examples are chosen to display each representative/universal archetype and do not describe the specific case constellation structure.

For example, the case of Shanghai Wujing in China suits to Figure 5a single center with one anchor entity of a coking plant with linked sectors of chemical plants (e.g., carbon, hydrogen peroxide, chlor-alkali) [78].

[56] studied the Rantasalmi Eco-industrial Park in Finland, which can represent the single center with periphery in Figure 5b. The IS cluster consists of mechanical wood processing industries with the single center of a log house manufacturer, whereas all the waste wood is recovered for the generation of heating and electricity for industries and the local community [56].

The case of the Kalundborg Symbiosis in Denmark matches to Figure 5c, as it comprises a core center with multiple anchor entities with periphery. The core center covers predominantly a power station, a pharmaceutical and wastewater treatment plant and an oil refinery, whereas the periphery is connected to agricultural farms, fish, fertilizer, gypsum board and cement production, Kalundborg city, nickel and vanadium recovery [53].

The case of Harjavalta Industrial Eco-Park in Finland represents the balanced IS system in Figure 5d, as the main participating entities maintain multiple resource interrelationships from the sectors of copper and nickel flash smelters, nickel chemical, hydrogen, sulphuric acid and energy production and the town of Harjavalta [58].

Figure 5e can be introduced by the case example of Händelö in Sweden, in which the local town, the CHP plant, ethanol and biogas plants are structured in a supply chain with main tie direction [82].

[44] studied the IS of the Nanning Sugar Industry in China, which incorporated affiliated companies centered around their core business of sugar production to (re-)process/circulate the residual and waste streams of the mother company, extending their own business to an IS supply chain with periphery which again is shaped as branched off IS supply chains, see Figure 5f. Enterprises of cane farming, paper, alcohol, health products and cement industry were all located at the upstream or the downstream of the main sugar production, which led to reduced costs and pollution controlling fees and environmental impacts, created new jobs and innovation for advanced business models, ensured the supply of raw materials and material quality [44].

[76] analyzed the case of Relvão Eco-Industrial Park in Portugal, which can be mapped to Figure 5g asymmetric IS system as this has no main trait formation. The main sectors are dealing with waste management and resource recovery (e.g., battery and plastic recycler, disassembler, waste management and wastewater treatment plants) and are linked to fertilizer, pulp and paper production and agricultural farms [76].

[78] investigated ten IS systems with the method of social network analysis (SNA), identifying the structure, connectivity, density and power relationships. They found out, that in China, most IS systems are joint-enterprise types, and are centered on one or a few large-scale enterprises (with core and affiliated relationships). [78] concluded that the entities involved interact strongly with each other, the input and output flows and their respective material exchanges are more balanced and transparent among the IS structure, because they belong to a single legal economic entity and lower the informational, trust, organizational and decision barriers. In contrast, during the development of other IS systems, most enterprises remained legally and economically independent, and the IS relationships among them were established (spontaneously) by means of contracts and agreements [78].

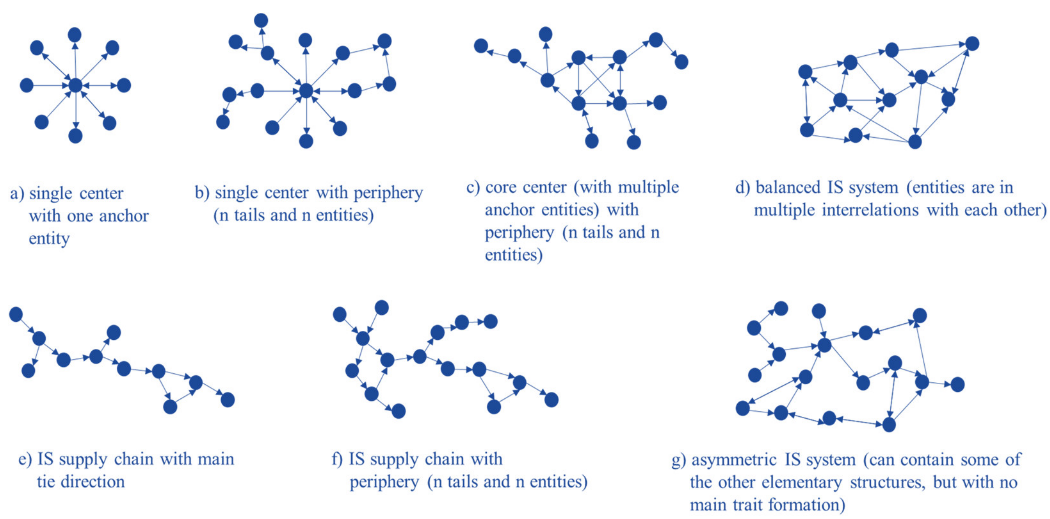



**Figure 5.** Classification of structural IS archetype formations.

### *3.2. Industrial Symbiosis Activities and Measures*

#### 3.2.1. Industrial Symbiosis Resource Exchanges

Based on the conducted cross-case analysis the following systematized IS activities were identified:

1. Non-material exchanges: sharing of knowledge/expertise (e.g., an experienced company in auditing of various corporate certifications or management methods such as change and lean management can share its expertise with less experienced companies), utilities/infrastructure (e.g., joint organization/usage of kindergartens, cafeterias, shuttle-services for employee commuting, etc.), joint management services (e.g., procurement of same resources, disposal/recycling processes). [83] studied the Landskrona Industrial Symbiosis Programme (LISP) in Sweden, in which inter-organizational collaboration comprised non-material synergies such as management routines, new business arrangements, collective bargaining, and envisioning joint goals towards sustainable development.
   More common in IS systems are physical resource exchanges of materials, energy and water:

1. Materials:
   - Secondary raw/substitute material exchanges: companies use waste flows of other entities as secondary raw/substitute, auxiliary and operating materials. [27] investigated an Austrian IS system, in which the manufacturer of cellulose insulation collected wastepaper from onsite companies to re-process it for material (re-)utilization. [57] presented a Finnish case study, in which a pulp mill fed its bark residues to a combined heat and power plant (CHP) for energetic utilization.
   - gaseous waste/aerosols: can be directly (or various substances are extracted out/treated beforehand) transferred to other companies as secondary raw, auxiliary and operating materials. [62] examined an Indian business cluster in Mysore, in which inter alia the CO2 emissions from a distillery are forwarded to a CO2 bottling facility. Aerosol waste flows such as (coal) fly ash can be inserted as cement [25,36] or soil additive [57,68].
   - sludge/slag: can be directly (or various substances are extracted out/treated beforehand) forwarded to other companies as secondary raw materials. [41] presented a Chinese IS case study of an iron and steel industry which transferred its blast furnace and steel slag to a cement company.

1. Energy:
   - (process/waste) heat/steam/cold: companies with excess/waste heat/cold/steam can pass on their heat/cold/steam flows to other entities [46,55,88,92]. [52] analyzed a case study in Denmark, in which various industries fed their waste heat flows into the district heating grids.
   - electricity: energy producing companies (as their core or side business, for example with an onsite CHP plant) transfer power to other entities. [58] showed a Finnish IS network, mainly covering copper and nickel flash smelters, nickel chemical producer, energy producer, hydrogen plant, sulphuric acid plant and the town of Harjavalta, which has implemented energy cascading and material exchanges.

2. Water:
   - (waste/process) water: companies forward their (process) water to other entities for direct (or in the meantime treated water) utilization. [44] presented a Chinese case study, in which industrial process and white water of paper production was recovered to re-utilize it in pulp production. Wastewater from a food processing company (e.g., olives, cereals, fruits and vegetables) can be further used for the fertilized irrigation of agricultural land [68,77] or further processed into a fertilizer product.

In all investigated 80 case studies material exchanges took place, in 78% of the case studies energy exchanges were recorded (biogas plants were included in an IS system in 15 of 80 case studies and 16 of 80 case studies incorporated a CHP power plant), 61% of the case studies comprised water exchanges (including wastewater) and 11% mentioned utility sharing and 9% knowledge exchange. So utility sharing and knowledge exchanges do not occur often in the examined case studies. However, it does not necessarily mean that there is no utility sharing and/or knowledge exchange in the IS systems, it only means that it was not investigated or explicitly mentioned in the case studies. But nevertheless, it can indicate that previous IS systems focus predominantly on physical resource exchanges. Figure 6 illustrates the frequency of detailed IS resource exchanges in the 80 case studies (whereas resource exchanges were included once they occur > = 5%). It points out that (hot) water (including wastewater) is the most frequent exchange type, followed by steam, sludge, blast furnace and steel slag, (coal) fly ash, heat, electricity, carbon dioxide, (metal) scraps and (waste) plastics. Energy-intensive industries, such as iron and steel, cement, etc. often use (plastic) wastes from local communities, municipalities and other industries for energetic (re-)utilization in their plants [41,70]. Especially (coal) fly ash and steam were passed on to cement plants and oil refineries. The cement, concrete and (road) construction industries appear to be main receiving sectors of various industrial wastes such as solid (mineral/metal and organic) waste streams (e.g., organic dried sewage sludge, steel and BF slag). Steam was mainly generated by power plants (including CHP plants), which was directly used for heating of various manufacturing processes. Materials with relatively high market values such as (precious) metals (e.g., copper, aluminum) or materials which are technically and economically easier to recycle (e.g., plastics, glass, paper) are more likely to be recovered for material and energetic re-utilization.

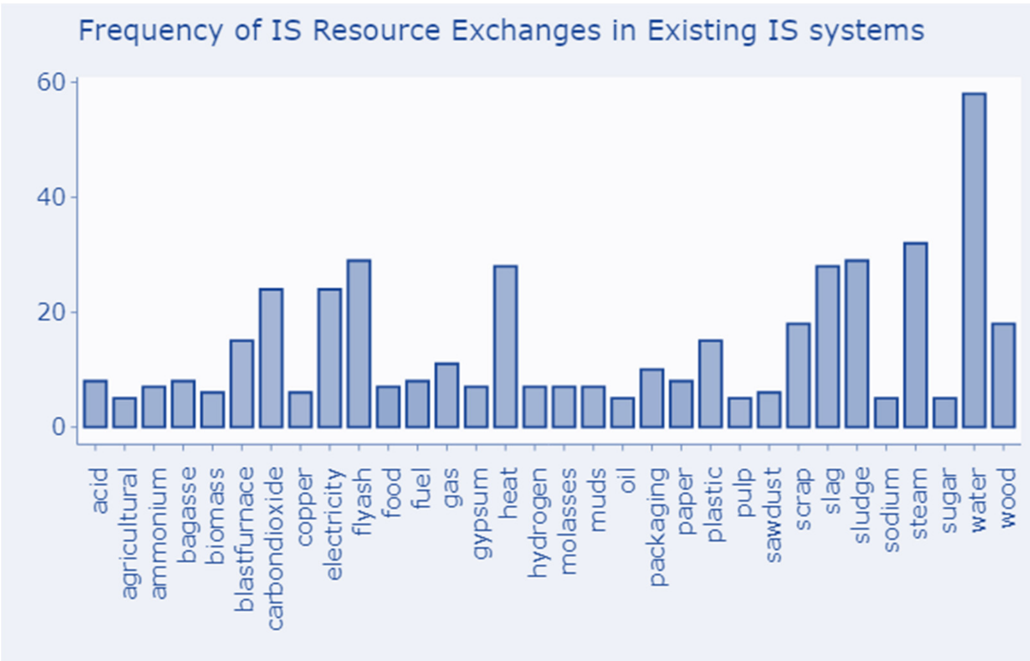



**Figure 6.** Frequency of IS resource exchanges in existing IS systems (resource exchanges with > = 5% occurrence were included).

### 3.2.2. Industrial Symbiosis Resource Exchange Catalog

In order to provide better knowledge diffusion and experience transfer, practical cases of IS and detailed physical resource exchanges (including material, water, energy) found in literature was pooled in an IS dataset (which can be the content basis for a relational database), creating a catalogue of IS resource exchanges and activities which can serve as elementary blueprint pieces. This systematized approach opens up the access from technology-enabling environments (e.g., IT-supported IS tools) to pool and (semi-)automatically process information/data in order to facilitate the identification of potential IS cooperation partners and further IS activities [16]. This recommendation can initialize further action of the business user to initiate business negotiations for possible IS connections among suitable cooperation partners. The recorded data entries of the MAESTRI database of IS resource exchanges were complemented with the additionally analyzed case studies to a total of 617 IS resource exchanges. The information/dataset contains information of specific IS measures, broken down by industrial sectors (e.g., NACE codes), differentiating providing and receiving sectors and which respective exchanged waste flows were processed into which secondary material/product. Table 2 shows an exemplary excerpt of the developed IS resource exchange catalog.

**Table 2.** Exemplary excerpt of the IS resource exchange catalog (alphabetically sorted by exchanged waste flow and providing sector).

| Providing Sector | Receiving Sector | Exchanged Waste Flow | Processed into/used as |
|---|---|---|---|
| automotive industry | aluminum smelter | aluminum scrap | aluminum |
| animal processing | biodiesel production | animal residues | biodiesel |
| CHP power plant | fertilizing industry | ash | fertilizer: ash pellets |
| sugar refinery | pulp plant | bagasse | pulp |
| pulp and paper plant | power plant | bark | biofuel |
| pulp mill | CHP power plant | bark | energy |
| pulp mill | pellet production | bark | pellets |
| iron and steel industry | cement industry | BF and steel slag | cement additive |
| sugar refinery | cement industry | bio sludge | cement additive |
| pulp plant | alkali recovery | black liquid | alkali |
| pulp production | boiler plant | bleaching water | heated water |
| CHP plant | landscaping | bottom ash | soil additive |
| power plant | bricks manufacturer | bottom ash | bricks additive |
| biogas plant | greenhouse | CO2 emissions | CO2 plant growth gas |
| burning facility | greenhouse | CO2 emissions | CO2 plant growth gas |
| distillery | CO2 bottling facility | CO2 emissions | CO2 raw material |
| ethanol production | algae production | CO2 emissions | algae |
| pulp and paper plant | calcium carbonate plant | CO2 emissions | calcium carbonate additive |
| power plant | cement & construction | coal fly ash | cement additive |
| aquaculture | power plant | cooling water | cooling water |
| cement industry | hospital | cooling water | cooling water |
| refinery | power plant | cooling water | process cooling water |
| algae production | fertilizing industry | dead algae/microbes | fertilizer |
| power plant | chemical industry | deminerlized water | process water |
| wastewater treatment plant | cement industry | dried sewage sludge | cement additive |
| hydropower plant | pulp and paper plant | electricity | process energy |
| biogas plant | agriculture | fermentation residuals | compost |
| aquaponic | compost facility | fish solids | compost |
| CHP power plant | cement industry | fly ash | cement additive |
| power plant | agriculture | fly ash | soil quality improvement and fertilizer |
| power plant | glass and glass-ceramic production | fly ash | ceramic additiv |
| power plant | production of bricks | fly ash | bricks additive |
| power plant | road construction | fly ash | concrete additive |
| chemical industry | plaster board manufacturer | gypsum | gypsum board |
| CHP power plant | cement industry | gypsum | cement additive |
| CHP plant | desalination plant | low pressure steam | process steam |
| animal farm | biogas plant | manure | biogas |
| animal farm | fertilizing industry | manure | manure pellets |
| sugar cane refinery | alcohol distillery | molasses | alcohol |
| algae ponds | fish farming | nutrient rich water | fish feeding |
| algae production | fish farm | nutrient rich water | fish |
| biogas plant | algae production | nutrient rich water | algae |
| fish farm | vegetable farm | nutrient rich water | vegetables |

| | | | |
|---|---|---|---|
| agroethanol plant | animal farming | organic residuals | fodder |
| agro-food industry | agriculture | organic residuals | fertilizer |
| biogas plant | agriculture | organic residuals | fertilizer |
| pulp and paper plant | fertilizing industry | organic residuals | fertilizer |
| fish farming | local farms | organic residues | animal feeding |
| local farms | biogas plant | organic waste | biogas |
| CHP power plant | chemical industry | steam | process steam |
| power plant | various industries | steam | process heat |
| automotive industry | metal casting | steel/iron scraps | steel/iron |
| various industries | steel industry | steel/iron scraps | steel/iron |
| power plant | industrial landfills | waste ash | stabilizer |
| power plant | road construction | waste ash | aggregate material |
| power plant | electricity production | waste heat | process heat |
| power plant | fish farm | waste heat | heat |
| power plant | olive mill | waste heat | process heat |
| power plant | urban entities | waste heat | district heating |
| CHP power plant | greenhouse | waste heat/steam | organic food |
| local communities | iron and steel industry | waste plastics | fuel material |
| local communities | waste-to-energy plant | waste plastics | power |
| agro-food industry | agriculture | waste water | fertilized irrigation |
| chlorine dioxide plant | calcium carbonate plant | waste water | process water |
| pig farming | biogas plant | waste water | biogas |
| power plant | various industries | waste water | process water |

## 4. Discussion and Conclusions

Existing IS tools have concentrated on IS identification and specific matchmakings among economic entities [11,12]. However, possible future scenarios such as zero waste parks/regions as well as corresponding transformation pathways from the actual to the desired target state are rarely or not covered by existing tools. This proposed IS tool facilitates the technology-enabling environment for IS initiation, management and continuous improvement as a mean to exhaustively exploit IS potentials for leveraging sustainable industrial development and to provide easy-to-use business support to industrial actors and to increase user friendliness and IS adoption in industrial systems, triggered by inter alia lack of knowledge of IS possibilities and lack of information sharing among companies. This study is embedded in an overarching project, dealing with the development of a holistic IT-supported IS tool covering an information exchange platform among industrial actors, system analysis (identification of IS potentials via quantitative methods such as Material Flow Analysis), transformation simulation (e.g., dynamic supply-demand match makings within an IS system) and sustainability goal-setting [16].

This paper has introduced the structural and systematic approach, how an IT-supported IS tool can deploy already existing information and to enable data-driven simulation of transformation pathways. It has been shown that similar IS sectoral partnerships and resource exchanges have recurrently formed in different regions and hence, generalizable patterns, elementary blueprints and structural units can be deduced from existing IS case studies. This work revealed that the fundamental functioning of an IS system mimics the essential mechanisms of ecological resource metabolisms, covering producers, primary/secondary/n consumers and destruents/remineralizers. The most frequent key sectors in IS systems comprise agriculture/aquaculture, power, pulp and paper, iron and steel, construction, chemical as well as waste treatment/recycling industries. Also repetitious resource exchanges and structural formations occurred in IS systems. Once this fundamental information base is incorporated and applied in an IT-supported IS tool, it enables the facilitated recommendation of potential IS partners and IS actions to optimize existing IS cases or to initiate IS development. Especially, first IS germ cells of key sectors/entities can be derived and connected to each other considering individual circumstances and (geographical) business environments.

The existing (scientific) literature and the corresponding knowledge about IS systems already provides a first basis for pooling such information in knowledge bases such as MAESTRI [24], to which IT-supported IS tools should have access in order to facilitate and outline further IS exchanges and connections [16,20,93]. Additionally, once the developed IS resource exchange catalog is linked to an IT-supported IS tool, in which companies can enter their production input-output information, specific recommendations for potential IS partners and respective IS resource exchanges can be suggested by mapping compatible input-output resource flows of the entered data and the underlying IS data base. The structural IS classification of IS systems is one of the crucial factors to create templates/blueprints for IS structures and IS actions, which can be used later in IT-supported IS tools. The as-is state can be matched with the as-shall or as-can states (blueprints), considering indicator systems with which the actual performance can be tracked towards the desired future target state [94], and corresponding IS activities and (missing) links between entities can be implemented in order to increase IS performance, system adaptability and resilience.

Future research should further elaborate (sector-specific) blueprint scenarios of (optimally utilized) IS systems in order to advance the technology-enabling environments of IT-supported IS tools. The development of generalizable templates/basic (sector-specific) blueprints is promising to significantly drive the dynamics and speed of (further) development of IS systems. Therefore, sector-specific material, water and energy blueprint profiles can be compiled as [95] specified in particular for a petrochemical refinery. This research revealed that previous IS studies have strongly focused on specific sectors such as chemical/pharmaceutical, (heavy) metal, cement, pulp and paper, sugar refining industries. This means that if future scientific studies explore IS systems that include sectors that have not or rarely been investigated so far, it would broaden the perspectives of IS application opportunities and this could be a further gain of knowledge to shed light on supplementary IS potentials and connection possibilities and may be additional key clusters and entities can be detected.

However, IS is mainly dealing with waste, residual and by-product flows which depend on company-performances and are therefore fluctuating in amount and quality. Within the production processes, flows of primary raw materials, operating and auxiliary materials and process water/steam can be contaminated with various substances. This complicates the recyclability, circularity and reutilization of materials, water and steam and can narrow the further IS cascading application field. [45] analyzed the Qijiang Industrial Park in China and pointed out that upstream resource exchanges influence the entire IS system to a large extent due to fluctuations in material flows and quality in particular, especially for downstream companies, it is made difficult to respond in short term in an adequate manner. This poses high vulnerability and risk factors relating to supply security and material/product quality. Building resource exchange networks may create vulnerabilities by a higher degree of interdependencies among the entities and their performances, so the power relations between the IS participants need to be considered carefully as well as the level of trust and how the IS community interfere with each other regarding transparency and information exchange [96,97]. Via an IT-supported IS tool information exchange concerning material and energy flow management (including quality and amounts) can be (partly) tackled in order to enable the companies to react properly and in a timely manner to variations. The resilience and sustainability of an IS system can be increased by establishing backup systems by introducing redundant or similar entities [97] and increasing the diversity and heterogeneous business settings, in order to ensure multi-functionality, flexibility and plasticity of the IS network [98]. [99] and [100] stated that the greater the inter-firm dependency among the companies in an IS network, the greater the risk of vulnerability and instability. Redundant entities with multiple connections in an IS context may support a higher resilience of the IS system, provided that the power relations are relatively balanced.

Nevertheless, planning, implementation and operation of IS activities need to be carefully and comprehensively evaluated. IS should not only be considered as an instrument to reduce resource scarcity and waste streams, but all sustainability dimensions (society, ecology, economy) should also be taken into account for further utilization and recycling options in order to avoid possible further negative consequences resulting from IS-induced activities. Socio-ecological-economic effects of IS measures should be assessed/estimated within and also beyond the IS scope in order to evaluate the overall sustainability effectiveness, as issues may be shifted out of the IS scope, and then may occur elsewhere.

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## 8. Paper 5: Web Tool for the Identification of Industrial Symbioses in Industrial Parks

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For better readability, better understanding and a logical structure of the research work, the original publications are inserted in each case.

# Web Tool for the Identification of Industrial Symbioses in Industrial Parks

**Anna Lütje, Sinéad Leber, Jonas Scholten, and Volker Wohlgemuth**

**Abstract** Industrial Symbiosis (IS) is a systemic and collaborative business approach to optimize cycles of material and energy by connecting the supply and demand of various industries. IS provides approaches for advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple utilization within industrial systems in order to increase resource productivity and efficiency. This study aims to present the conceptual IT-supported IS tool and its corresponding prototype, developed for the identification of IS opportunities in IPs. This IS tool serves as an IS facilitating platform, providing transparency among market players and proposing potential cooperation partners according to selectable criteria (e.g. geographical radius, material properties, material quality, purchase quantity, delivery period). So this IS tool builds the technology-enabled environment for the processes of first screening of IS possibilities and initiation for further complex business-driven negotiations and agreements for long-term IS business relationships. The central core of the web application is the analysis and modelling of material and energy flows, which refer to the entire industrial park as well as to individual companies. Methods of Material Flow Analysis (MFA) and Material Flow Cost Accounting (MFCA) are used to identify possible input–output- and supply–demand matchings. The second central core of the web application is the identification of existing and potential cooperation partners for the development of IS networks. In order to achieve this, a combinatorial approach of Social Network

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Analysis (SNA) and a deposited geographical map are inserted, so that same suppliers and recycling/disposal companies can be detected.

**Keywords** Industrial ecology · Industrial symbiosis · Material flow analysis · Material flow cost accounting · Social network analysis · Life cycle assessment

## 1 Introduction

Human activities have been major driving forces of global changes such as climate change, environmental pollution and increasing scarcity of resources, so that today´s era is called "the Anthropocene" [8]. In order to meet these challenges adequately, concepts such as Industrial Symbiosis (IS) are seen as a substantial key enabling factor for resource efficiency and circularity, contributing to the trajectory of sustainable development [14].

IS is covered by the scientific field of Industrial Ecology [5]. It is a systemic and collaborative business approach to optimize cycles of material and energy by connecting the supply and demand of various industries, while generating ecological, technical, social and economic benefits [4, 6, 10, 15, 19, 35, 39]. IS provides approaches for advanced circular/cascading systems, in which the energy and material flows are prolonged for multiple utilization within industrial systems in order to increase resource productivity and efficiency. The most cited definition is from Chertow [5], "IS engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and byproducts". According to Lombardi and Laybourn [24], "IS engages diverse organizations in a network to foster eco innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes".

In the IS context, many companies approach their "waste" streams as new business opportunities or extended business models. For example, waste heat/exceeding steam can be forwarded to other companies, turning the originator company to an energy supplier [13, 31, 33, 42]. A smeltery in China recovered raw materials out of gaseous waste/aerosol, sludge/mud and solid waste [43]. The Guitang Group in China used their sludge as the calcium carbonate feedstock to a new cement plant, while reducing residual and waste flows, solving a disposal problem [44]. Gaseous waste streams such as fly ash can be used as cement additive [9, 12, 17] or soil additive [2, 32]. Waste water from a company that processes food such as olives, cereals, fruit and vegetables can be further used as fertilizer [7, 32], and for the irrigation of agricultural land, the respective organic residual (solid) waste can be further processed to animal/fish feeding (material utilization) [1, 3] or biogas and biofuel (energetic utilization) [1].

The aim of an IS is to establish virtually closed energy and material cycles/extended cascading systems through cooperation between companies. Industrial agglomerations and industrial parks (IPs) can be considered a favourable starting point to generate a first germ cell [6, 16, 20, 37, 41], as IS is predominantly based on collaboration and synergistic opportunities revealed by geographical proximity [6]. IS exhausted IPs mimic ecological dynamic systems concerning a development of a resilient system and an optimized use of resources by the cascading utilization of material and energy flows.

IS can occur spontaneously due to economic motivation, but just up to a certain point, then it needs to be further driven to exhaust its full potential [31]. This implies a systematized approach for cross-industry collaboration within a community through inter-organizational communication and information exchange [18, 22, 34]. The more complex the system to be considered, the more relevant computer-aided solutions become in order to map energetic and material movements or to facilitate cross-company collaborations. In order to identify and develop IS, instruments from the field of Information and Communication Technologies (ICT) play a central role. So the inter-company information flows for the identification of IS opportunities can be facilitated by an information platform [21, 36].

## 2 Method

This study aims to present the conceptual IT-supported IS tool and its corresponding prototype, developed for the identification of IS opportunities in IPs. The content concept of the IS tool has been designed based on previous research activities, concerning the development of an initial basic framework for the software/system development process phase of requirements engineering (RE), also called requirements analysis. RE is one of the main activities of the software or system development process, which defines the requirements for the system to be developed with the help of a systematic procedure from the project idea to the goals to a complete set of requirements. This was underpinned by extensive systematic literature research and analysis of existing case studies as well as interviews with IS experts and practitioners.

This study addresses the development of the IT concept and prototyping phase for an IT-supported IS tool for the identification of IS opportunities in IPs. Prototyping is an essential part of the software design process. A prototype is a first version of a software system that demonstrates concepts, tries out design options and learns more about upcoming problems and respective possible solutions. A prototype is particularly suitable for identifying changes that may be necessary or potential improvements at an early stage. During prototyping, both the graphical representation and the core functionalities of the system can be implemented. Prototypes provide the starting point for new requirements and can identify areas with strengths and weaknesses in the software. In addition, a prototype can be used to investigate the behavior of the system when several functionalities are combined (Fig. 1).

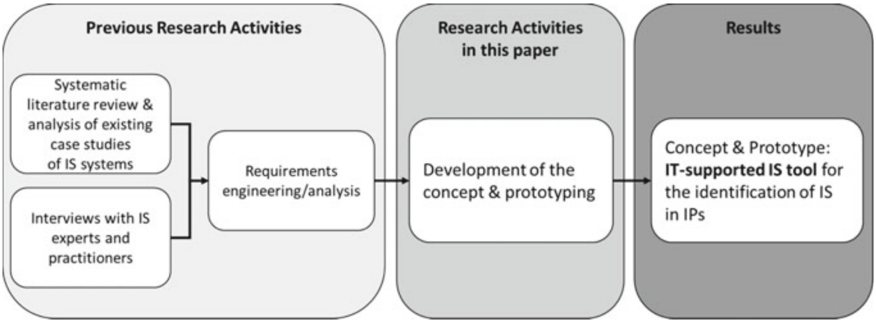


**Fig. 1** Design of the research approach

# 3 Web Tool for the Identification of Industrial Symbioses Within an Industrial Park

## *3.1 Quantitative Methods for IS Identification*

Various quantitative methods can be applied for the process of identifying IS opportunities. A previously conducted analysis of existing IS case studies revealed, that common methods such as emergy analysis,[1] Material Flow Analysis (MFA),[2] Material Flow Cost Accounting (MFCA),[3] Life Cycle Assessment (LCA)[4] and Social Network Analysis (SNA)[5] were used to investigate the current state system and to deduce possible IS activities [26]. For instance, Bain et al. [2] conducted a case study in an industrial area in South India, using MFA to analyze the recovery, reuse and recycling of industrial residuals and to identify existing symbiotic connections within this area. Applying MFA, Chertow [7] did a multiyear investigation of industrial sites in Puerto Rico between 2001 and 2007, in order to develop IS scenarios focused on utility sharing, joint service provision and by-product exchanges. LCA was used by

[1]Emergy is an expression of all the energy consumed in direct and indirect transformations in the processes to generate a product or service, therefore emergy analysis converts the thermodynamic basis of all forms of energy, resources and human services into equivalents of a single form of energy (usually solar emjoules).

[2]MFA quantifies the input and output flows and stocks of materials and energy for each process of the system under consideration in physical units (e.g. kg).

[3]MFCA quantifies the input and output flows and stocks of materials and energy in physical and monetary units, especially the material losses, non-/by-product and waste flows are associated an economic value (standardized to ISO 14051).

[4]LCA quantifies the input and output flows and stocks of materials and energy of entire product life cycles and assesses the associated environmental impacts, such as global warming and eutrophication potential (standardized to ISO 14040).

[5]SNA investigates social structures of networks and characterizes elements within the network in terms of nodes (e.g. individual actors, companies, people) and the connecting ties or links (relationships or interactions).

Sokka et al. [35] who studied a Finnish Forest Industry Complex around a pulp and paper mill to identify potential IS synergies. While Martin [30] explored IS in the biofuel industry in Sweden with LCA to detect IS opportunities and quantify the environmental performance. Ulhasanah and Goto [38] used a combinatorial approach of MFA, MFCA and LCA in a case study of cement production in Indonesia, in order to derive IS activities.

The research methods on IS systems have been extended from energy and material flows and its associated costs to social aspects, broadening the perspective to collaboration and the relationships among the IS entities, which can profoundly determine the effectiveness and efficiency of the entire IS system. SNA provides the investigation of the structure of IS systems and the (power) relationships of the entities involved. For instance, Song et al. [36] analyzed the Gujiao eco-industrial park in China and found out that SNA reveals IS potentials to develop more synergy linkages, identifying key/anchor actors in the network and their relation/context to exchanges of material, energy and (waste) water. Doménech and Davies [11] analyzed trust relationships in production or business networks in an empirical study of IS, using SNA.

## *3.2 Prototype*

All previously collected information was incorporated into the design and prototypical development of the IT-supported IS tool. The prototypical web application was developed according to the REST[6] architecture. Technologies, frameworks and interfaces (APIs) from the field of web development were used such as AngularJS[7] (referring to the MVC architecture[8]), Spring Boot,[9] MySQL[10] and JPA.[11]

[6]REST stands for REpresentational State Transfer, enabling the realization of web services. Data is transferred via HTTP without the need for an additional transport layer such as SOAP (Simple Object Access Protocol) or session management via cookies. The clients send their requests to the server. The server processes them and returns a corresponding response. This communication is regarded in REST as a transfer of representations of resources. An application can interact with a resource if it knows the identifier of the resource and the action to be performed and can interpret the format of the returned information (representation). The server makes its external capabilities available not as services, but as resources that are identified via a URI (Uniform Resource Identifier).

[7]AngularJS is a library written in JavaScript for the development of dynamic web applications.

[8]The MVC architecture is a programming methodology with three core components: a model, a view, and a controller.

[9]Spring Boot is an open source framework for simplified application development with Java/Java EE.

[10]MySQL is a relational database management system. It is available as open source software as well as a commercial enterprise version for various operating systems and forms the basis for many dynamic websites.

[11]Java Persistence API (JPA) enables database access and object-relational mapping. This enables an object-oriented view of tables and relationships in a relational database management system (RDBMS). JPA can be used to work with objects instead of SQL statements.

In the front end, the service is designed as a single page application (SPA) to give it a look and feel of a desktop program. This is realised by using the Angular JS framework. It provides the developer with an MVC pattern, which makes it easy to extend, maintain and test the software.

For prototype development it is vital to have a running service as quickly as possible without lacking a proper design. Therefore, the choice was made to use the CSS framework Bootstrap. A responsive design can be implemented by making a few changes to the HTML elements.

Sankey.js is an extension of the Data Driven Documents (D3) library and is used to create the Sankey diagrams. The interactive image is generated by a JSON definition. With the D3 library as the core later implementations of new graphical representations can easily be integrated.

Leaflet is an open source library which enables the creation of interactive maps. By adding the ui-leaflet directive into Angular JS the map can be directly integrated with the <leaflet> HTML tag. It allows the display of tiled web maps which can be zoomed and dragged by mouse. As an overlay its features vary from clickable markers, CSS popups, circles and polygons.

The core of the backend is created by Spring Boot. The Java framework includes the implementation of a RESTful Webservice as well as dependency injection. Endpoints can be easily configured. The communication between client and server are made in JSON format. Data persistence is achieved by a MySQL database. By using the Java Persistance API (JPA) changes can be made by sending objects instead of SQL queries.

The web application serves as a tool for the analysis of material and energy flows as well as the detection of possible symbiosis partners within an industrial area. In this concept, three common methods were chosen (MFA, MFCA, SNA) due to simplified first IS screening reasons and user-friendly applicability of the IS tool. The implementation of other methods such as LCA or emergy analysis requires specific method knowledge and access to external (costly) environmental databases, that is why these kind of methods are not considered in this proposed IS tool.

The central core of the application is the analysis and modelling of material and energy flows, which refer to the entire industrial site as well as to individual companies. Methods of MFA and MFCA are used in the web application to identify possible input–output- and supply–demand matchings [25].

The second central core of the application is the identification of existing and potential cooperation partners for the development of IS networks. In order to achieve this, a combinatorial approach of SNA and a deposited geographical map are inserted, so that same suppliers and recycling/disposal companies can be detected, hence, the IS network can be intensified [27].

The web tool supports the functions of:

(1) Evaluating material and energy movements in companies and the entire IP (MFA)
(2) Evaluating the costs of material and energy flows in each company, especially waste streams are attributed an economic value (MFCA)

(3) Identification of material and energy related input–output and supply–demand matchings among the participating entities
(4) Visualizing the structure and relationships of the entities, embedded in an IP, and connected external suppliers or disposal/recycling companies (SNA)
(5) Identification and recommendation of possible cooperation partners for IS exchange relationships

The visualization of the results is carried out by means of balance sheets, sankey diagrams, material cost matrices and sociograms. The functional requirements determined can be found in Table 1.

The first implementation step of the frontend component takes place with the input mask “Company”, where the user enters the master data of the company. The location of the company can be selected from a dropdown menu, as the user can only access locations that have already been created. After all fields are filled in, the data can be transmitted to the backend via HTTP request by pressing the “save” button and then stored in the database.

The next step is the implementation of the “Materialmanagement” workspace. Here the user can create new material and energy inputs or outputs in the database as well as the material management of the company. Figure 2 shows the input mask for creating new processes with respective energy and material inputs/outputs in the database.

Using the buttons on the left side, the user can navigate between the work areas “Add Inputs”, “Add Outputs” and “Management of processes and material". The company can be created as a black box[12] or in a detailed level with individual production lines and processes. Once the user decides to map the company with the internal structure, she/he is forwarded to the application area “Create production line". Here, individual production lines of the company can be created. The data of the production line consists of the name and a description. This data is created in the database after pressing the “save” button. Furthermore, a list of the created production lines is created on the page. By clicking on the corresponding button, processes can then be added to the production line. The production line can also be edited and deleted. If a production line is deleted that already contains process data, all linked data from the database are also deleted. Here the user can create a new process for the previously selected production line. The data of a process consists of the name, the production line, an item or index and the system costs incurred. By specifying an index, you can determine the position of the process in the system during evaluation using the MFCA method. As soon as a process has been created, inputs and outputs can be added to it. The inputs and outputs can be selected via a dropdown menu with a search function. The data for this are loaded from the database. At this point, the user can only access inputs or outputs that already exist in the database, so they need to be created beforehand. The selected inputs or outputs can then be supplemented with process-specific data. This includes, among other things, the quantity, the costs and the classification (i.e. the environmental impact, e.g. $CO_2$ emissions, of the input or output). In addition, it can be indicated whether the input or output is available

[12]Black box: the company is displayed as one process with all input and output flows.

**Table 1** Overview of determined functional requirements

| Nr. | User Administration (UA) |
|---|---|
| UA 1 | To protect corporate data, only authenticated users should be able to use the application |
| UA 2 | The administrator should be able to register users via a special form |
| UA 3 | To use the application, the user must log in via the login window |
| *Enterprise Administration (EA)* | |
| EA 1 | Every user should be able to create and edit specific data about the company |
| *Material and Energy Management (MEM)* | |
| MEM 1 | Every user should be able to create new materials and energies (thermal and electrical) and store them in the database |
| MEM 2 | Every user should have the possibility to create one or more production lines for the company |
| MEM 3 | Every user should have the possibility to add one or more processes to existing production lines |
| MEM 4 | Materials and energies can be added as input and output to created processes |
| MEM 5 | Each material/energy should be able to be released by the user for exchange relationships |
| MEM 6 | Individual product lines can be edited and deleted by the user |
| MEM 7 | Individual processes can be edited and deleted by the user |
| *Map functions (MF)* | |
| MF 1 | All companies in the industrial estate are to be displayed on a map |
| MF 2 | It should be possible to filter the display of the companies on the map according to certain criteria:<br>• Cooperation partners<br>• Materials offered<br>• geographical radius<br>• Etc |
| *Data Display and Visualization (DDV)* | |
| DDV 1 | Material and energy data should be presented in input–output balances |
| DDV 1.1 | Input–output balances should be prepared for the entire company as well as for individual processes |
| DDV 1.2 | All approved materials and energies (cross-company) should be presented in a site balance |

(continued)

**Table 1** (continued)

| Nr. | User Administration (UA) |
|---|---|
| DDV 1.3 | Particularly hazardous/non-hazardous materials should be color-coded |
| DDV 2 | Material and energy data should be displayed in Sankey diagrams |
| DDV 2.1 | Sankey diagrams should be created for the entire company as well as for individual processes |
| DDV 2.2 | All approved materials and energies (cross-company) are to be displayed in a Sankey diagram for the site |
| DDV 2.3 | All Sankey diagrams should represent both physical and monetary units of measure |
| DDV 3 | Material and energy data from created production lines should be displayed in material cost matrices |
| DDV 4 | Potential and actual cooperation links between companies should be presented in sociograms |
| *Analysis Function (AF)* | |
| AF 1 | The data are to be evaluated according to the MFA method and thus material and energy movements in the company and location are to be determined |
| AF 2 | The data are to be evaluated according to the MFCA method and thus cost saving potentials in the company or processes are to be pointed out |
| AF 3 | Match-making algorithms will be used to determine possible cooperations between companies on the basis of material and energy data |
| *Dashboard (DB)* | |
| DB 1 | Every user should see a dashboard with important information on the start page of the web application |
| DB 2 | The dashboard should display data such as:<br>• Material loss and use<br>• $CO_2$ emissions<br>• Possible symbiosis partners<br>• Number of cooperation partners |

for exchange relations with other enterprises. All entered energy and material data in physical units relate to the method of MFA and all cost-related data are required for MFCA.

A dashboard has been implemented on the start page of the application to provide an overview of the important key figures (Fig. 3). The dashboard shows, for example, possible cooperation partners, actual material losses and the company's $CO_2$ emissions. Starting from the start page, the user can navigate to all evaluations of the energy and material flows and the balance sheet. If the user has mapped the company with internal processes, process balances are displayed for each process created. A

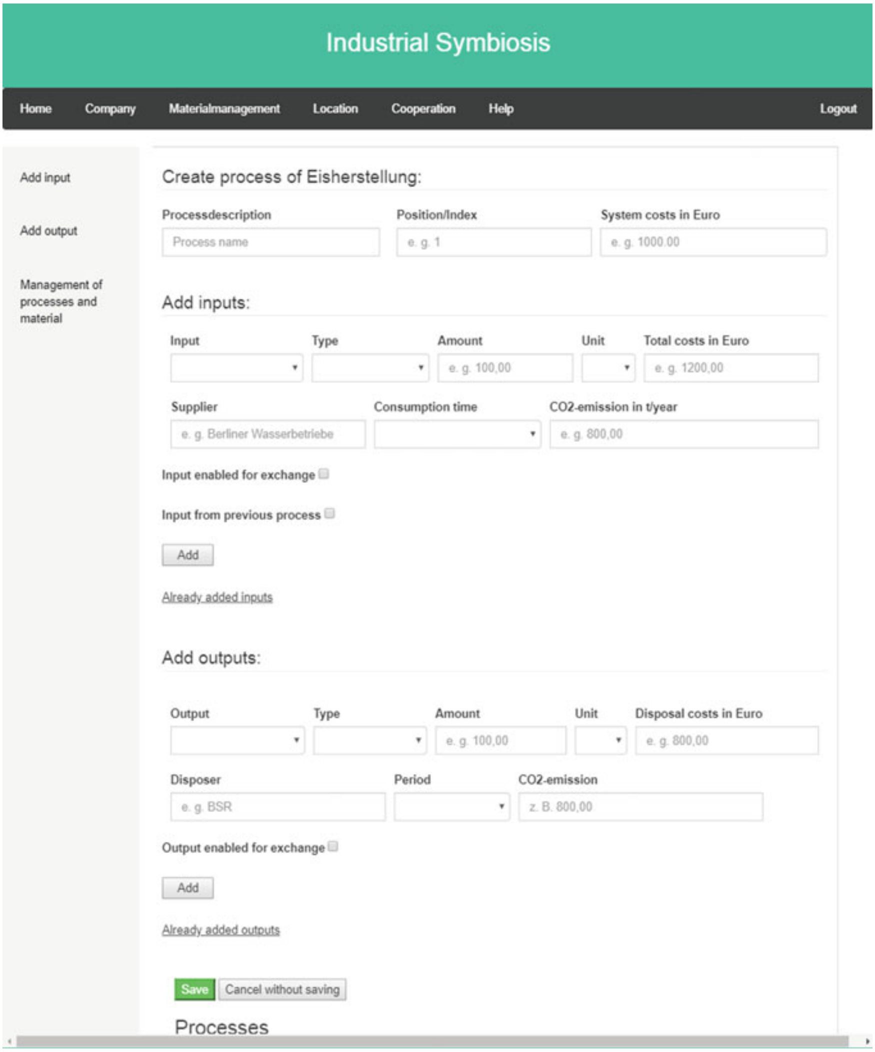


**Fig. 2** Input mask for creating new processes with respective energy and material inputs/outputs

further representation of the material and energy evaluation was realized by implementing sankey diagrams,[13] representing quantity flows in physical and monetary units. By selecting the tab "Cost matrix" the user navigates to the MFCA evaluation (Fig. 4).

[13]A Sankey diagram is a graphical representation of quantity flows with arrows proportional to the quantity.

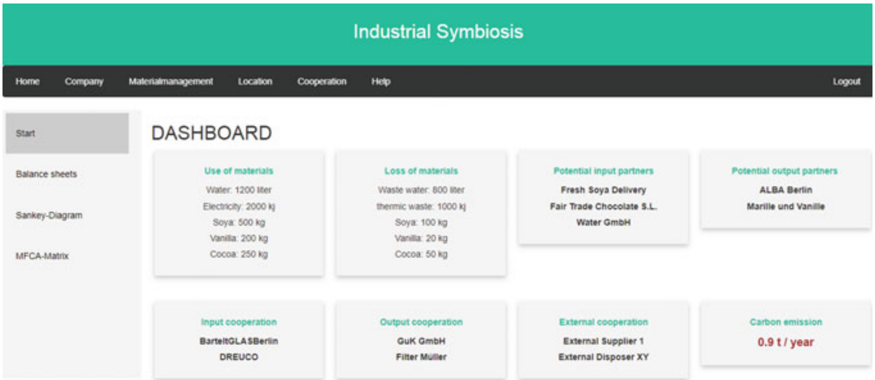


**Fig. 3** Dashboard

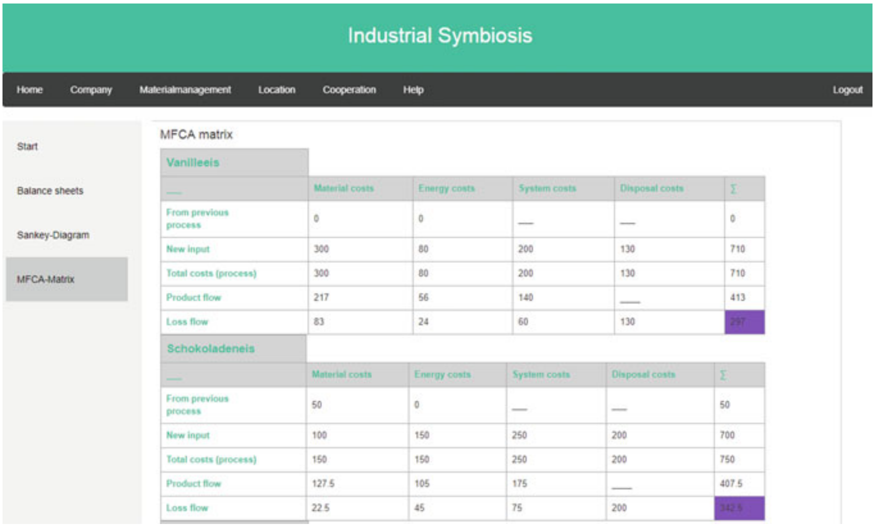


**Fig. 4** MFCA matrix

Another important implementation step is the workspace “cooperation". Possible cooperation partners are proposed on the first page of this web area. The potential symbiosis partners are determined in the backend component by corresponding queries of the database and transmitted to the frontend. For energy and material input–output resource matchmaking among the entities, the user can define a percentage value for the maximum deviation in quantity (Fig. 5). Potential exchange relationships that lie outside this limit are not displayed, so only companies that are within the critical quantity are shown. In the tab “Show own cooperations”, a list of the own cooperation partners is displayed. This list includes the companies in the industrial area with which an exchange relationship already exists, which can additionally be

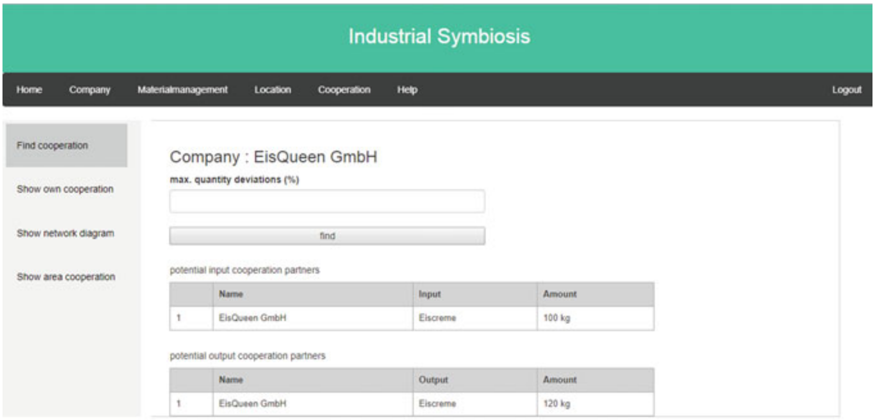


**Fig. 5** Workspace “Cooperation”

represented by sociograms. On the one hand, a sociogram is created for connections to all companies, including external suppliers and disposal, and on the other hand for internal relationships within the industrial site.

Figure 6 shows the location function on the implemented leaflet map. In this work area the user can see all companies of the industrial area on the map by Default. Using the buttons on the left side, the user can select which markers are to be displayed, for example all cooperation partners or companies of the same branch. The last two buttons allow the display of companies based on required inputs or offered outputs. Markers are created by converting the stored addresses of the corresponding companies into geocoordinates (latitude and longitude) and transmitting them to the frontend.

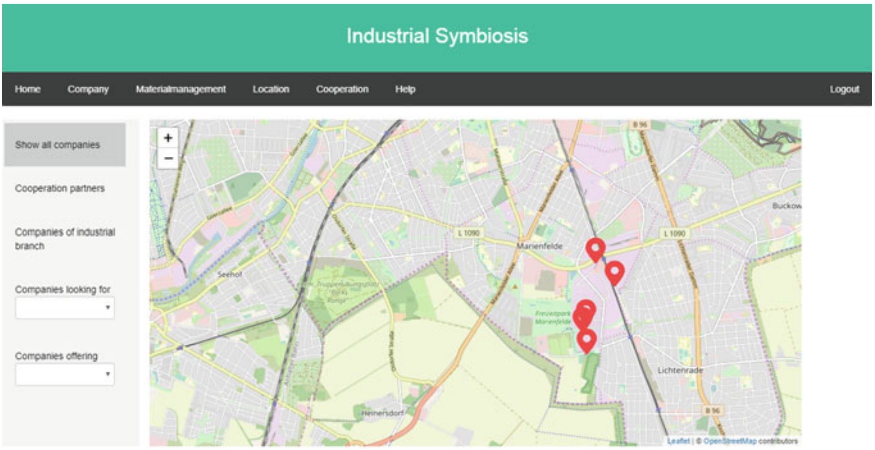


**Fig. 6** Map function

The web application allows on the one hand a company-specific analysis and on the other hand an analysis of the entire industrial site with methods such as MFA, MFCA and SNA. Every participating company can use the tool for internal evaluation and decision making and an established overarching organizational unit of the industrial park can use aggregated information for (resource/environmental) site management as well as the expansion of IS networks.

## 4 Discussion and Concluding Impulses for Future Research

This IS tool serves as an IS facilitating platform, providing transparency among market players and proposing potential cooperation partners according to selectable criteria (e.g. geographical radius, material properties, material quality, purchase quantity, delivery period). So this IS tool builds the technology-enabled environment for the processes of first screening of IS possibilities and initiation for further complex business-driven negotiations and agreements for long-term IS business relationships, regarding security of supply of resources, including possible (seasonal, temporal and qualitative) variability and fluctuations, medium to long-term agreements on price and quality.

Considering all entities as actors operating in a commercial market, the motivation of implementing IS activities is predominantly economy-driven, that is why this presented IS tool incorporates the method of MFCA to represent the economic values of all energy and material flows, including waste streams. This can lead to higher awareness of potential energy, material and cost savings, so that the (successive) process of reducing waste flows is given a higher priority. Furthermore, potential risks of for example misuse of information [40] or starting barriers were tackled in advance by taking respective precautions of specifying access and editing rights. For example, a company can exploit the web tool for internal resource evaluation and optimization reasons, but can adjust the tool settings so that they do not participate in the overarching level of IS detection.

In order to continuously monitor and control the progress of an IS development, an indicator system can be set up to evaluate the IS performance [28]. By defining goals for the IP, for example zero waste-, zero emission-, $CO_2$ neutral-park, the trajectory and corresponding (IS) measures can be compiled in a roadmap. So further research in the IS context should address the development of a (key performance) indicator system.

Additionally, the examination of recurring patterns of commonly exchanged materials, IS activities and IS structural formations opens up the use of Artificial Intelligence (AI) techniques [27]. As well as the complementary use of AI techniques can turn an IT-supported IS tool into a comprehensive and holistic instrument with which future scenarios and transformation paths from the actual system state to the desired future vision can be simulated [27, 29].

By the digitalization of data collection and processes, IPs may evolve into Smart Industrial Parks (SIP) with intelligence monitoring, information processing and risk prevention [23]. So Environmental Management Information Systems (EMIS) need to be established within IPs to provide a reliable data basis for comprehensive valuable information and substantiated decision making, so that companies can track their economic, social and ecological performance through advanced and intelligent ICT solutions.

**Declaration of Interest** The authors declare no conflict of interest.

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## 9. Discussion & Concluding Impulses

IS can occur spontaneously due to economic motivation, but just up to a certain point, then it needs to be further driven to exhaust its full potential (Mirata, 2004). This work focuses the technology-enabled environment for IS system analysis, transformation simulation and goal-setting in order to enable and facilitate IS in IPs. Therefore, a first prototype has been already conceptualized and developed. The proposed concept for a holistic IT-supported IS tool goes beyond the previous approaches of system analysis and IS identification as well as information and collaboration platform. The innovative elements in this approach are, on the one hand, the extension of perspective to future visions/scenarios and goal setting for elaborating target-oriented transformation pathways and, on the other hand, the inclusion of supporting simulation and modelling techniques of exploring various transformation pathways from the actual state of an IP to the desired goal state of an IS system. So, topics of system analysis and IS identification are well recorded in the scientific and non-scientific literature, but there are still profound research gaps in the fields of normative and transformative knowledge, which should be prioritized in future research activities referring IS systems. Especially the elaboration of quantifiable goals (which can be in line with the Sustainable Development Goals (SDGs) of the United Nations (UN) and/or Science Based Targets (SBT)), and the development of a corresponding roadmap with concrete IS measures should be addressed intensively in this research field.

Further development and refinement of an IT-supported IS tool requires additional research especially in the field of building up respective databases in order to exhaust the full potential of the presented IT-supported IS tool. The buildup of such an (international) IS database should be part of future research and forms a cornerstone for the inclusion of system dynamics and even Artificial Intelligence (AI) methods as well as supporting expert systems, which accelerate IS identification. Information and data on IS structure and morphology as well as material exchanges can be basic properties that an Artificial Neural Network can use to characterize and classify IS network types. The prerequisite for the use of

expert systems and AI techniques is essentially the development of (relational) databases that can be compiled from previous (non-)scientific literature.
Existing IS tools have concentrated on IS identification and specific matchmakings among economic entities (Grant et al., 2010, Maqbool et al., 2019). However, possible future scenarios such as zero waste parks/regions as well as corresponding transformation pathways from the actual to the desired target state are rarely or not covered by existing tools. This proposed IS tool facilitates the technology-enabling environment for IS initiation, management and continuous improvement as a mean to exhaustively exploit IS potentials for leveraging sustainable industrial development and to provide easy-to-use business support to industrial actors and to increase user friendliness and IS adoption in industrial systems, triggered by inter alia lack of knowledge of IS possibilities and lack of information sharing among companies.
This research work had introduced the structural and systematic approach, how an IT-supported IS tool can deploy already existing information and to enable data-driven simulation of transformation pathways. The existing (scientific) literature and the corresponding knowledge about IS systems already provides a first basis for pooling such information in knowledge bases such as MAESTRI (Evans et al., 2017), to which IT-supported IS tools should have access in order to facilitate and outline further IS exchanges and connections (Lütje et al., 2019). Additionally, once the developed IS resource exchange catalog is linked to an IT-supported IS tool, in which companies can enter their production input-output information, specific recommendations for potential IS partners and respective IS resource exchanges can be suggested by mapping compatible input-output resource flows of the entered data and the underlying IS data base. The structural IS classification of IS systems is one of the crucial factors to create templates/blueprints for IS structures and IS actions, which can be used later in IT-supported IS tools. The as-is state can be matched with the as-shall or as-can states (blueprints), considering indicator systems with which the actual performance can be tracked towards the desired future target state, and corresponding IS activities and (missing) links between entities can be

implemented in order to increase IS performance, system adaptability and resilience.

Future research should further elaborate (sector-specific) blueprint scenarios of (optimally utilized) IS systems in order to advance the technology-enabling environments of IT-supported IS tools. The development of generalizable templates/basic (sector-specific) blueprints is promising to significantly drive the dynamics and speed of (further) development of IS systems. Therefore, sector-specific material, water and energy blueprint profiles can be compiled as Cervo et al. (2019) specified in particular for a petrochemical refinery. This research revealed that previous IS studies have strongly focused on specific sectors such as chemical/pharmaceutical, (heavy) metal, cement, pulp and paper, sugar refining industries. This means that if future scientific studies explore IS systems that include sectors that have not or rarely been investigated so far, it would broaden the perspectives of IS application opportunities and this could be a further gain of knowledge to shed light on supplementary IS potentials and connection possibilities and may be additional key clusters and entities can be detected.

Such an IT-supported IS tool could be considered as a small cogwheel in a complex large system, a point of contact and leverage point to contribute to the trajectory of sustainable development, facilitating the expansion and intensification of interconnectedness and intra- and inter-organizational collaboration, while enabling safe operating cooperation environments.

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## Appendix A

I declare that all the information given in this appendix is true and correct, both individually and in its entirety.

### Overview of the scientific author contribution of Anna Rohde-Lütje

I hereby submit a statement of authorship for each article submitted, explaining my own individual scientific contribution to the preparation of the article and the proportion of my own contribution in relation to the contribution of the other co-authors as a whole.

I hereby confirm that the information in the following table is true and correct.

| Paper Nr. | All articles are published and were peer-reviewed | Own contribution in terms of content | Share of own contribution |
|---|---|---|---|
| 1 | A. Lütje, M. Willenbacher, A. Möller, V. Wohlgemuth, "Enabling the Identification of Industrial Symbiosis (IS) through Information Communication Technology (ICT)", 2019, **Proceedings of the 52nd Hawaii International Conference on System Sciences (HICSS),** pp. 709-719, ISBN: 978-0-9981331-2-6, doi: http://hdl.handle.net/10125/59511<br>→ Technical presentation given to an international audience of experts at the specialist conferences at the 52nd Hawaii International Conference on System Sciences (HICSS) in Maui (8.-11. January 2019): https://scholarspace.manoa.hawaii.edu/handle/10125/59440, https://scholarspace.manoa.hawaii.edu/handle/10125/59511, Title: „Enabling the Identification of Industrial Symbiosis through ICT" and the EnviroInfo in Munich (5.-7. September 2018): http://www.enviroinfo2018.eu/conference-agenda/, Title: „A preliminary concept for an IT-supported | conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration | **85%** |

| | | | |
|---|---|---|---|
| | Industrial Symbiosis (IS) tool using extended Material Flow Cost Accounting (MFCA) – Impulses for Environmental Management Information Systems (EMIS)“ | | |
| **2** | A. Lütje, V. Wohlgemuth, “Requirements Engineering for an Industrial Symbiosis Tool for Industrial Parks Covering System Analysis, Transformation Simulation and Goal Setting”, 2020, **Administrative Sciences (MDPI – Open Access)**, 10(1):10. https://doi.org/10.3390/admsci10010010 | conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration | **90%** |
| **3** | A. Lütje, V. Wohlgemuth, “Tracking Sustainability Targets with Quantitative Indicator Systems for Performance Measurement of Industrial Symbiosis in Industrial Parks”, 2020, **Administrative Sciences (MDPI – Open Access)**, 10(1):3. https://doi.org/10.3390/admsci10010003 | conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration | **90%** |
| **4** | A. Rohde-Lütje, V. Wohlgemuth, “Recurring Patterns and Blueprints of Industrial Symbioses as Structural Units for an IT Tool”, 2020, **Sustainability (MDPI –** | conceptualization, methodology, | **90%** |

| | | | |
|---|---|---|---|
| | **Open Access)**, 12(19):8280. https://doi.org/10.3390/su12198280 | validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration | |
| **5** | A. Lütje, S. Leber, J. Scholten, V. Wohlgemuth, "Web Tool for the Identification of Industrial Symbioses in Industrial Parks", in: A. Kamilaris, V. Wohlgemuth, K. Karatzas, I.N. Athanasiadis (eds), Advances and New Trends in Environmental Informatics, 2021, Progress in IS. **Springer**, Cham. https://doi.org/10.1007/978-3-030-61969-5_2 | conceptualization, methodology, validation, investigation, writing—original draft preparation, writing—review and editing, supervision, project administration | **70%** |

**Signature Anna Rohde-Lütje**